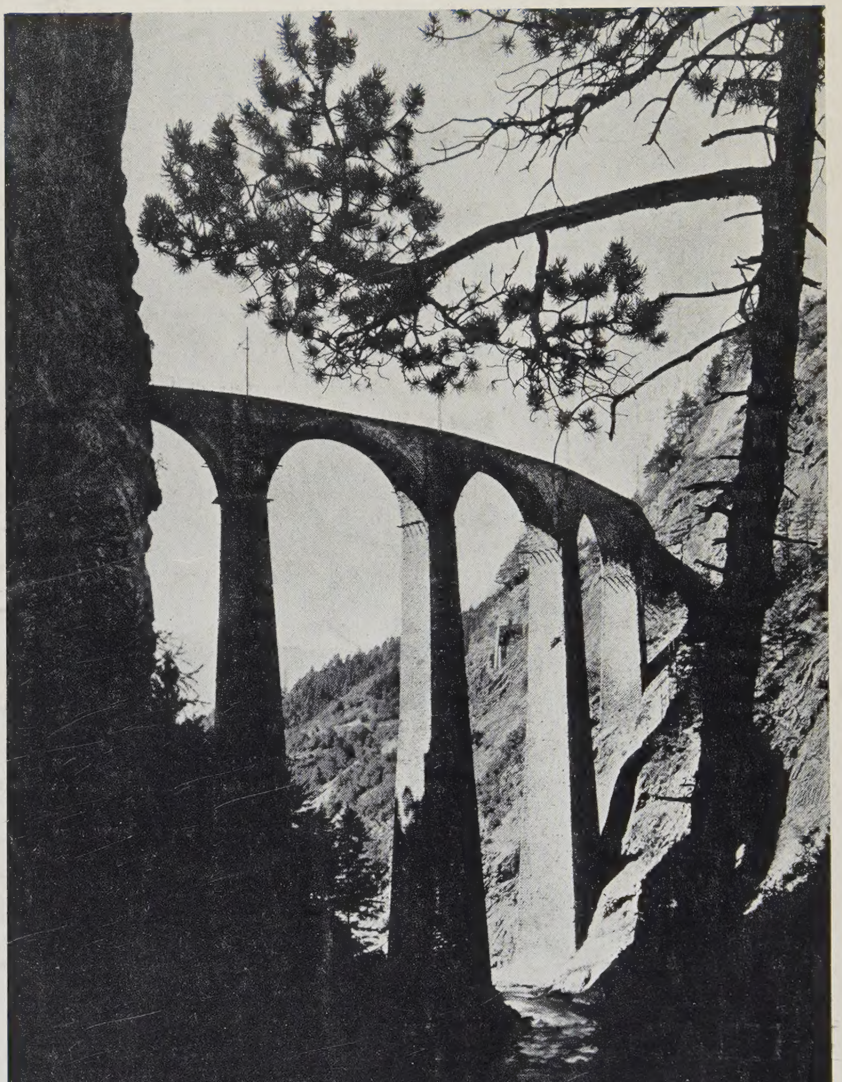
# Electrical Engineering

September
1934



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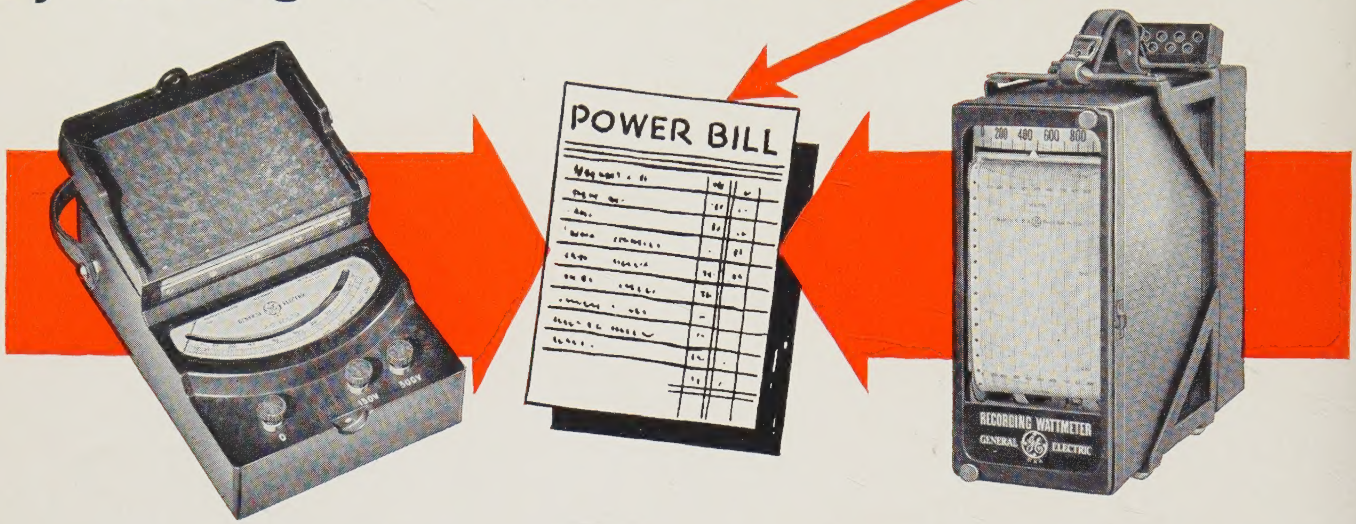


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# Recent Theories of Ferromagnetism

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**Recent advances in ferromagnetic theory, which are outlined briefly in this article, are concerned principally with the effect of elastic deformation on magnetic properties and the related magnetostriction. This is the ninth of a series of special articles reviewing contemporary advances in several of the more important and rapidly advancing fields of science that are of especial interest to electrical engineers, and prepared under sponsorship of the A.I.E.E. committee on education.**

NOT so very long ago ferromagnetism was merely one of the many curious and mystifying properties possessed by certain types of solids, too complicated to be of particular interest to scientists and, until the spread of electricity, of little practical importance except in the mariner's compass. Today, the subject is of great interest not only to the engineer, who has found many ways of using ferromagnetic properties and has developed new alloys that are far more satisfactory than the more common ferromagnetic materials, but also to the physicist. It seems very probable that ferromagnetism soon will be an important tool in the study of the fundamental theory and structure of metals.

It is proposed to outline in this article the progress that has been made in the understanding of ferromagnetism during the past few years. Since the successes have been confined to a small part of the subject, it may be well before entering upon a more detailed exposition to point out the general character of the experimental facts, so that the reader may see the recent contributions, important as they are, in a reasonable perspective.

One of the important facts about ferromagnetic materials is that their magnetic properties change radically with temperature. However, discussion of those properties, especially that part of especial interest to engineers, may be limited to room temperatures. Suffice it to say that temperature dependence of those properties which are understood at normal temperatures may be explained qualitatively at least. The most important quantitative results in this regard are contained in the Weiss equation

$$\frac{I_s}{I_o} = \tanh \frac{aI_s}{T} \qquad (1)$$

relating the saturation value of the magnetization $I_s$ at any temperature $T$ to the saturation value at the absolute zero of temperature, $I_o$, and certain atomic theory constants represented by the symbol $a$. For a more complete discussion of eq 1 the reader is referred to any book on ferromagnetism, for instance, "Magnetism and Atomic Structure" by E. C. Stoner.

At normal temperatures, then, the behavior of ordinary soft ferromagnetic materials may be divided conveniently into 2 parts. In small fields, of the order of one oersted or less, there are usually hysteresis effects, i. e., the magnetization is not determined uniquely by the external field, but depends also on the previous magnetization. This is the magnetic range of interest primarily in the transmission of signals, as in telegraph or telephone lines, where the energy available for magnetizing fields is limited. The discussion in the following pages will be limited to phenomena not involving hysteresis, and therefore will omit a large part of that interesting and important phenomena. In larger fields hysteresis effects are usually negligible—magnetization approaches saturation reversibly. Recent developments in theory have been useful chiefly in this range, and have had practical applications in the development of materials for power machinery, where both large and small fields are involved. In addition to the soft ferromagnetic materials, there are magnetically hard materials, the permanent magnets, which at present will have to be left completely out of the discussion.

Further, of very great importance is the effect of elastic deformation on magnetic properties and the related magnetostriction, or deformation caused by magnetization. This phenomenon can be treated by the new theories within the previously mentioned limitations—in the absence of hysteresis effects. Other phenomena, such as the effect of magnetization on elastic constants, on electrical resistance, etc., can be treated by the methods to be outlined with the same order of accuracy as magnetostrictive effects, but will not be discussed further in this paper. For details and further references see a review by the author in *Metallwirtschaft,* v. 12, 1933, p. 720, 735.

## Model of a Ferromagnetic Substance

Without going into detail, or justifying the procedure on the basis of atomic theory, an array of elementary permanent magnets of atomic dimensions having a marked tendency to be parallel to their neighbors will be used as a model of a ferromagnetic substance for purposes of this discussion. In the absence of other restraining forces these elementary units will point in the direction of any applied field, because by doing so they reduce their energy in the field to a minimum and at the same time satisfy their tendency of being parallel to their neighbors. In the absence of external fields they may break up into groups pointing in various directions, in which condition their resultant magnetization is

indeterminate. As already explained, in very small fields hysteresis effects usually are pronounced, and these effects will be left out of the discussion. Magnetization of the model will proceed as in the curve marked [100] in Fig. 2.

Magnetization curves for ordinary ferromagnetic materials do not resemble the curves assumed for this model; but it has been found that single ferromagnetic crystals, when magnetized in certain particular crystallographic directions, do behave very much like the model. For simplicity attention will be confined to iron, a cubic crystal. Similar results have been obtained for other substances and presumably hold equally well for solid solutions. The customary designation of the principal axes is shown in Fig. 1. In Fig. 2 are shown magnetization curves for polycrystalline iron as well as for a single crystal magnetized in the 3 principal crystallographic directions. It may be seen that only along a tetragonal

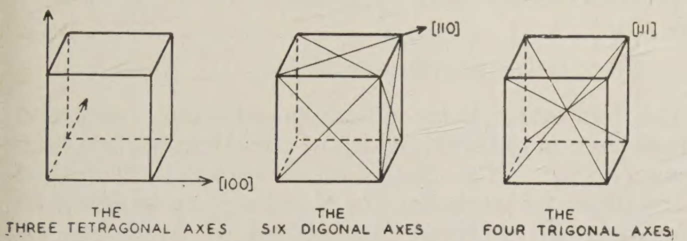



**Fig. 1. The principal axes in cubic crystals**

axis does the actual curve approach the theoretical curve of the model. A theoretical interpretation for all these curves has been worked out by N. S. Akulov (*Zeit. für Physik*, v. 67, 1931, p. 794, and many more articles in the same journal); his results are shown in solid lines in Fig. 2. Experimental ob-

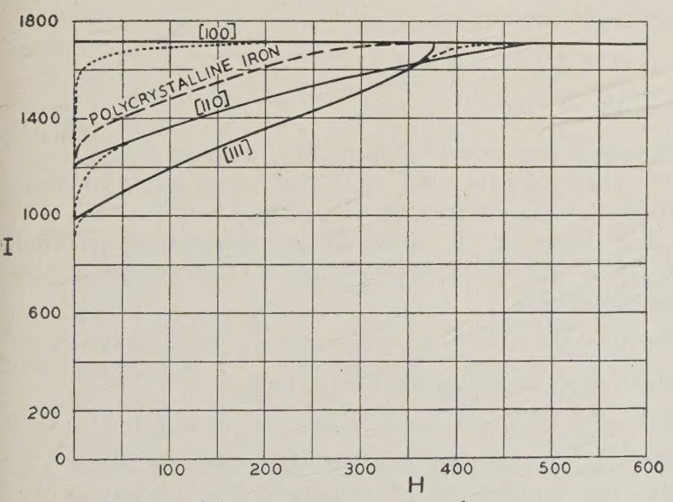



**Fig. 2. Magnetization curves of iron**

servations are in agreement with the theoretical curves except as shown by broken lines. The curve for polycrystalline material may be considered as the average of the curves obtained for all possible crystallographic orientations. The theoretical curve for polycrystalline material never has been calculated.

## Magnetization of Perfect Crystals

Akulov's theory is based upon the proposed model, modified by the addition of crystallographic symmetry. Since magnetization proceeds practically to saturation in very small fields only if these are applied parallel to one of the 3 tetragonal axes, it may be assumed that the elementary magnets are constrained by some type of force to point along one of these axes, and that work must be done to rotate them into other directions. An easy check on this suggestion is the following: If a small field be applied parallel to a digonal or trigonal axis, the resultant magnetization in the direction of $H$ must be given by

$$I_{[110]} = I_s \frac{1}{\sqrt{2}} = \frac{1{,}710}{1.414} = 1{,}210$$

$$I_{[111]} = I_s \frac{1}{\sqrt{3}} = \frac{1{,}710}{1.732} = 990$$

as may be seen readily from the diagram in Fig. 3. That these magnetizations are found experimentally may be seen in Fig. 2. The tetragonal axes are called the directions of easy magnetization. If a field be applied in any direction, magnetization will proceed to saturation in the direction of the nearest tetragonal axis. A further increase in the component of $I$ parallel to $H$ can take place only by a rotation of the direction of magnetization. Of the forces opposing such a rotation little can be said beyond the fact that their existence and order of magnitude falls quite within the limits predicted by the quantum theory of atomic phenomena.

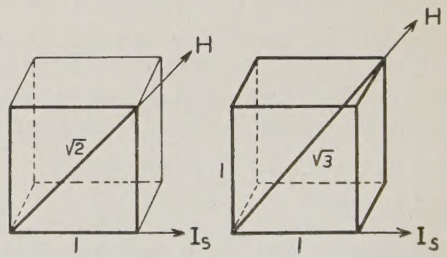
Instead of dealing with forces, it is more convenient to consider $E_\theta$, the energy per unit volume of a crystal, as a function of the direction of magnetization. Supposing one could take hold of the saturated magnetization, how much work would have to be done to rotate it from some standard orientation, say [100], to any other given by the direction cosines $\alpha_i$, $\alpha_j$, $\alpha_k$, measured with respect to the cubic axes of the crystal? Expanding $E_\theta$ in powers of $\alpha$ gives a general expression of the form

$$\begin{aligned} E_\theta = a &+ \\ & b_i\alpha_i + b_j\alpha_j + b_k\alpha_k + \\ & c_{ij}\alpha_i^2 + c_{ij}\alpha_i\alpha_j + \ldots\ldots + \\ & d_{iii}\alpha_i^3 + d_{iij}\alpha_i^2\alpha_j + \ldots\ldots + \\ & e_{iiii}\alpha_i^4 + \ldots\ldots + e_{iijj}\alpha_i^2\alpha_j^2 + \ldots\ldots \end{aligned}$$

where $a$, $b$, etc., are arbitrary constants.

Remembering that $\alpha_i^2 + \alpha_j^2 + \alpha_k^2 = 1$ and that $E_\theta$ must have cubic symmetry, or that it must have

**Fig. 3. Shows that the component of Is along digonal or trigonal axis is $I_s/\sqrt{2}$ and $I_s/\sqrt{3}$, respectively**




the same value for crystallographically similar directions of magnetization, as for instance $\alpha_i = 1$, $\alpha_j = 0$, $\alpha_k = 0$, or $\alpha_i = 0$, $\alpha_j = 1$, $\alpha_k = 0$, or $\alpha_i = 0$,

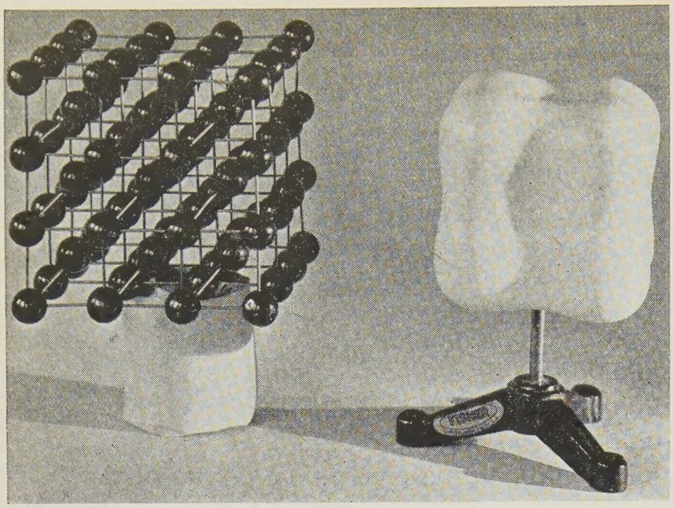


Fig. 4 (left). Model of an iron crystal, and a plaster model representing $E_\theta$, the energy required to magnetize this crystal in different directions, as described in the text

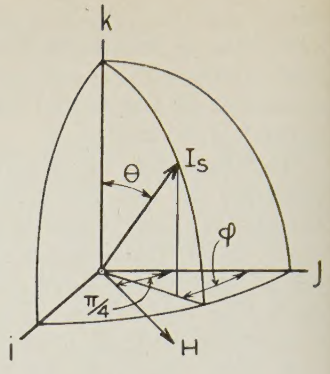



Fig. 5 (right). Diagram illustrating the transformation in eq 5

$\alpha_j = 0$, $\alpha_k = 1$, the most general expression involving powers of $\alpha$ not higher than the fourth is found to be

$$E_\theta = 2c(\alpha_i^2\alpha_j^2 + \alpha_j^2\alpha_k^2 + \alpha_k^2\alpha_i^2) + \text{constant}$$
$$= c\sum_{i,j,k}{}' \alpha_i^2\alpha_j^2 + \text{constant} \tag{2}$$

$c$ being an arbitrary constant. Figure 4 shows a plaster model of $E_\theta$ in which the length of the radius from the middle of the model to the surface in any direction represents the energy of the crystal when magnetized to saturation in that direction. In the model $c$ is chosen positive. This makes the hollows of the figure (directions of easy magnetization) fall parallel to the tetragonal axes, as in iron, and humps (directions of most difficult magnetization) parallel to the trigonal axes. In the presence of a magnetic field a further term must be added to the energy, the total being

$$E_\theta = \text{constant} + c\sum{}' \alpha_i^2\alpha_j^2 - I_sH\cos\psi \tag{3}$$

$\psi$ being the angle between $I_s$ and $H$. In order to find the actual direction of magnetization in any given field it is necessary to find for what direction (or what values of $\alpha_i$, $\alpha_j$, $\alpha_k$) $E_\theta$ has its lowest or minimum value. This is the most stable direction of magnetization, and from it follows at once the component of $I_s$ in the direction of $H$. For example, to compute the magnetization for any value of $H$ applied along the [110] direction, it is convenient to rewrite eq 3 in polar coördinates

$$\alpha_i = \sin\theta\sin\varphi \qquad \alpha_j = \sin\theta\cos\varphi \qquad \alpha_k = \theta \tag{4}$$

Magnetizing force $H$ is applied in the direction $\theta = \pi/2$, $\varphi = \pi/4$ (see Fig. 5). It is apparent that for any positive values of $H$, the minimum of $E_\theta$ must lie in the plane $\theta = \pi/2$, so that eqs 4 reduce to

$$\alpha_i = \sin\varphi \qquad \alpha_j = \cos\varphi \qquad \alpha_k = 0$$

and finally

$$E_\theta = 2c\sin^2\varphi\cos^2\varphi - I_sH\cos(\pi/4 - \varphi) + \text{constant}$$

which has a minimum when $\varphi$ satisfies the equation

$$\frac{\partial E_\theta}{\partial\varphi} = 0 = 4c\sin\varphi\cos\varphi(\cos^2\varphi - \sin^2\varphi) - I_sH\sin(\pi/4 - \varphi)$$

Putting $I = I_s\cos(\pi/4 - \varphi)$ this easily can be shown to reduce to

$$H = -4c\frac{I}{I_s^2} + 8c\frac{I^3}{I_s^4} \tag{5}$$

The value of $c$ chosen to give the close agreement between theory and experiment shown in Fig. 2 is

$c = 2.15 \times 10^5$ ergs per cubic centimeter

The hysteresis loops of reasonably pure annealed iron have in general a width of considerably less than one oersted. The discrepancies between theoretical and observed curves in Fig. 2 in fields up to about 50 oersteds are therefore not caused by hysteresis effects, and will be discussed after the effect of elastic deformation on magnetization has been considered.

## Magnetization of Homogeneously Distorted Crystals

The elastic distortion of a crystal may be represented by means of a tensor $A_{ij}$, which gives the coördinates of a point after the distortion ($x'$, $y'$, $z'$) in terms of its coördinates before the distortion by means of the equations

$$x' = (1 + A_{ii})x + A_{ij}y + A_{ik}z$$
$$y' = A_{ji}x + (1 + A_{jj})y + A_{jk}z$$
$$z' = A_{ki}x + A_{kj}y + (1 + A_{kk})z$$

(A tensor is a group of numbers, such as $A_{ii}$, $A_{ij}$, . . . etc., that may be used as in the foregoing equations to express the distortion of a solid.)

For instance, if there is an elongation parallel to the $x$ axis of amount $e$, and a contraction in the $y$-$z$ plane $e/2$,

$$x' = (1 + e)x \qquad y' = (1 - e/2)y \qquad z' = (1 - e/2)z$$

which may be obtained by putting

$$A_{ii} = e \qquad A_{jj} = A_{kk} = -e/2 \qquad A_{ij} = A_{ji} = \ldots = 0$$

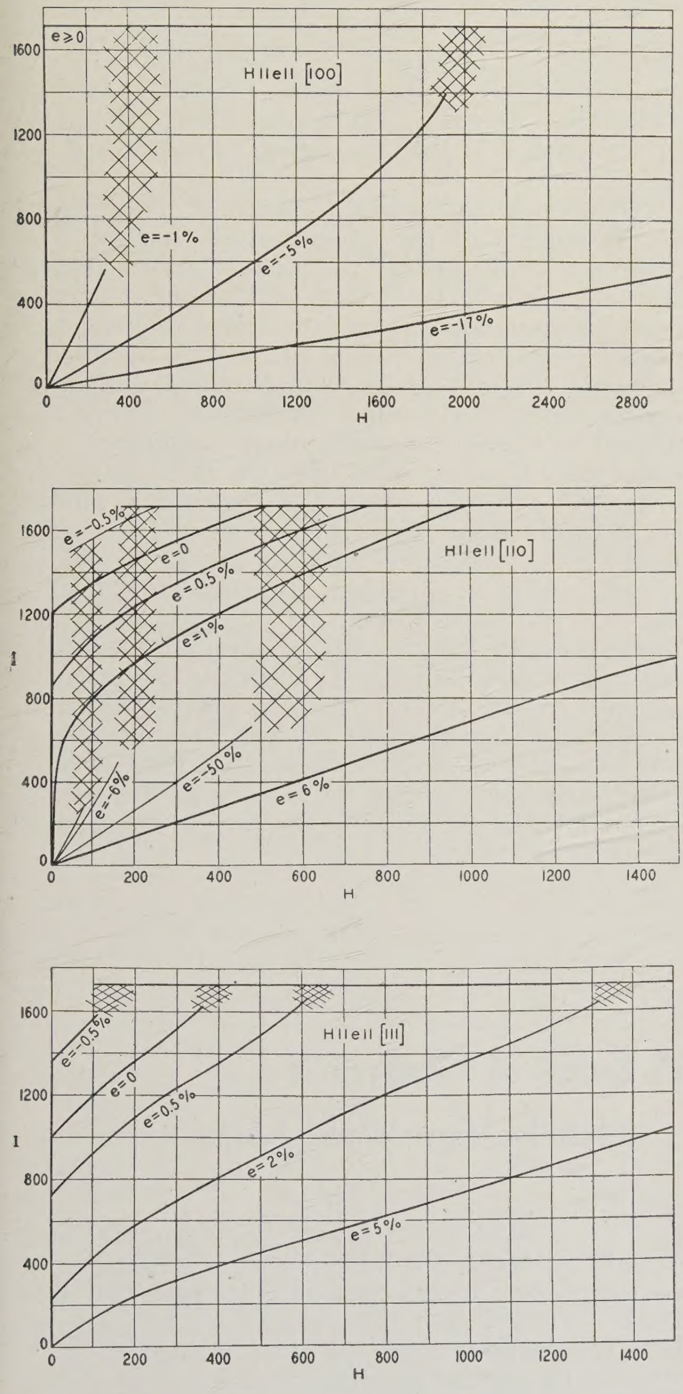
It can be shown readily that such a distortion involves no change of volume. For reference the

**Table**

| | |
|---|---|
| Elongation parallel to [100] | $A_{ii} = e$, $A_{jj} = A_{kk} = -e/2$ |
| Elongation parallel to [110] | $A_{ii} = A_{jj} = \frac{e}{4}$, $A_{kk} = -e/2$, $A_{ij} = A_{ji} = \frac{3e}{4}$ |
| Elongation parallel to [111] | $A_{ij} = A_{ji} = A_{jk} = A_{kj} = A_{ki} = A_{ik} = e/2$ |

tensor components of a distortion of this type in a cubic crystal whose tetragonal axes are parallel to the $x$, $y$, and $z$ axes of the coördinate system used are given in Table I.

The procedure outlined for obtaining the energy of a crystal as a function of the direction of magnetization may be applied equally well to distorted crystals; it is necessary merely to add in the expansion terms involving products of $A_{ij}$ and $\alpha_i$, etc. Doing so, and limiting the operation to the simplest terms of the expansion, the most general expression for $E_\theta$ having the desired cubic symmetry is found to be




**Figs. 6 to 8. Magnetization curves of iron crystals elastically distorted by tension in various crystallographic directions**

$$E_\theta = c\sum{}'\alpha_i^2\alpha_j^2 + K_1[A_{ii}\alpha_i^2 + A_{jj}\alpha_j^2 + A_{kk}\alpha_k^2] + K_2[(A_{ij}+A_{ji})\alpha_i\alpha_j + (A_{jk} + A_{kj})\alpha_j\alpha_k + (A_{ki} + A_{ik})\alpha_i\alpha_k] - I_sH\cos\psi$$
$$= c\sum{}'\alpha_i^2\alpha_j^2 + K_1\sum A_{ii}\alpha_i^2 + K_2\sum{}'A_{ij}\alpha_i\alpha_j - I_sH\cos\psi \quad (6)$$

The magnetization curve of a crystal elastically distorted in any manner describable by the tensor $A_{ij}$ now can be calculated by the same processes, merely using the more complete expression for $E_\theta$, provided the values of constants $K_1$ and $K_2$ suitable for iron are known. How these constants may be evaluated from data on magnetostriction will be shown in the next section. The result is

$K_1 = -3.06 \times 10^7$ ergs per cubic centimeter
$K_2 = 2.85 \times 10^7$ ergs per cubic centimeter

Magnetization curves for iron crystals elongated in each of the 3 principal directions are shown in Figs. 6 to 8. The values of $A_{ij}$ used are those shown in Table I. Only very small elastic distortions can be given a single crystal and these, in general, would not have the simple form given in Table I. The curves are intended merely to indicate the type of result to be expected. For certain values of $H$ and $e$ the function $E_\theta$ has several minima of equal or almost equal energy. In such cases the procedure outlined becomes ambiguous, and this fact is indicated by the cross-hatched part of the curves. A comparison of these curves with experiment cannot be made as no experimental data are available. The theory of distorted crystals was advanced by R. Becker (*Zeit. für Physik*, v. 62, 1930 p. 253, and subsequent articles with collaborators in the same journal; also F. Bitter, *Physical Review* v. 43, 1933, p. 655). He and his collaborators have checked certain predictions with observations on polycrystalline material, especially nickel.

## Magnetostriction

When the magnetization of an iron crystal changes, its shape changes also. This change of shape is called magnetostriction; it can be calculated for rotations of the direction of magnetization from eq 6. The forces required to produce the distortion $A_{ij}$ are given by a tensor $F_{ij}$ defined by the relations:

$$F_{ij} = \frac{\partial E}{\partial A_{ij}} \quad (7)$$

$E$ being the total energy of distortion of the crystal, $E_\theta$ plus the elastic energy $E_{el}$

$$E_{el} = \frac{c_{11}}{2}\sum A_{ij}^2 + \frac{c_{12}}{2}\sum{}'A_{ii}A_{jj} + c_{44}\sum{}'A_{ij}^2$$

where the elastic constants have in iron the values

$c_{11} = 0.237 \times 10^{13}$ $c_{12} = 0.141 \times 10^{13}$
$c_{44} = 0.116 \times 10^{13}$ ergs per cubic centimeter

The question is, what are the distortions of the crystal for any given direction of magnetization that will make all the external forces $F_{ij}$ defined by eq 7 vanish? There are 9 equations to solve which will give the 9 tensor components defining the shape of the sample as functions of $\alpha_i$, $\alpha_j$, $\alpha_k$. Instead of these results it is more convenient to use the change in length per unit length of a sample, $\delta l/l$, measured in a direction given by the direction cosines $\beta_i$, $\beta_j$, $\beta_k$, caused by a change in magnetization from any

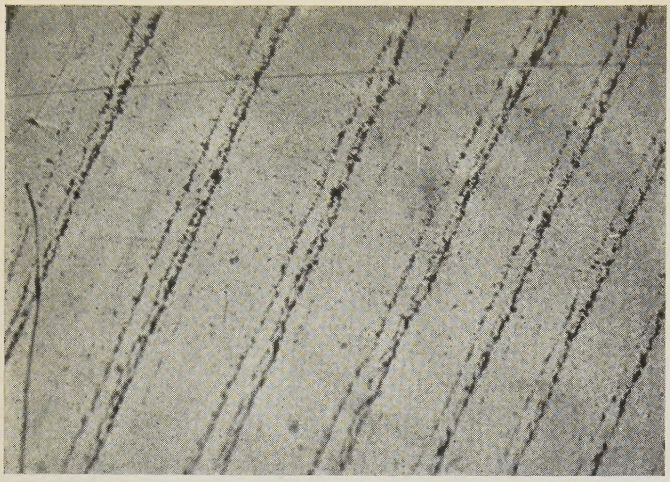


Fig. 9. Magnetic pattern on a nickel crystal. Direction of applied magnetic field ⟶

given original state to the final state given by $\alpha_i$, $\alpha_j$, $\alpha_k$. Carrying out this operation gives

$$\frac{\delta l}{l} = \sum A_{ii}\beta_i^2 + \sum{}' A_{ij}\beta_i\beta_j + \text{constant} \tag{8}$$

$$= \kappa_0 + \kappa_1 \sum \alpha_i^2\beta_i^2 + \sum{}' \alpha_i\alpha_j\beta_i\beta_j$$

$$\kappa_1 = -\frac{K_1}{c_{11} - c_{12}} \qquad \kappa_2 = -\frac{K_2}{2c_{44}}$$

To illustrate the application of eq 8, consider the change in length in the direction of magnetization resulting from magnetization to saturation along a tetragonal axis. In this case $\alpha_i = \beta_i = 1$, $\alpha_j = \alpha_k = \beta_j = \beta_k = 0$, and consequently $\delta l/l = \kappa_0 + \kappa_1$. The constants $\kappa_0$, $\kappa_1$, and $\kappa_2$ may be evaluated by a comparison with experiment; for iron they are found to be

$$\kappa_0 = -15.5 \times 10^{-6} \qquad \kappa_1 = 32.0 \times 10^{-6} \qquad \kappa_2 = -12.3 \times 10^{-6}$$

From these and the elastic constants, $K_1$ and $K_2$ can be evaluated. Agreement between eq 8 and experiment is fair, but it is possible that a close check requires that further terms in the expansion of $E_\theta$ be taken into account. The available experimental data are not sufficiently consistent to settle this point.

## Concluding Remarks

In the discussion so far 8 arbitrary constants have been used. The saturation value of the magnetization $I_s$ can be accounted for more or less accurately by atomic theory, especially as regards its variation with temperature. Of general interest is the conclusion that the magnetic elements giving rise to magnetization are spinning electrons somewhere near the outer surface of the atoms. The constant $c$ measuring the binding energy between the direction of magnetization and the lattice also can be accounted for roughly on the basis of atomic theory. The other 6 constants, 3 elastic and 3 determining magnetostriction, are purely empirical. One may expect that present notions of atomic interactions can account for them, but the computations are so involved that no successful attempts so far have been made.

The discrepancies between theory and experiment shown in Fig. 2 in fields up to 50 oersteds in all probability can be ascribed to the fact that the crystals on which observations were made were not perfect. Assuming that actual crystals contain randomly oriented distortions varying from point to point within a crystal, it is possible to calculate, using Becker's theory, the resulting magnetization curve. Such calculations show that random distortions not only can account for the rounded curves found experimentally (Fig. 2), but also can predict certain peculiarities at low flux densities which in fact do exist. The conclusion is that in those ferromagnetic crystals so far examined, random distortions of the order of, or somewhat larger than, magnetostrictive distortions are present. (Further discussion of this point will appear shortly in a paper by the author in the *Proceedings* of the Royal Society.)

In closing it may be well to point out, that in spite of the success of the comparatively simple ideas discussed in this article, the phenomena themselves are more complicated. It is well known that magnetic powders may be used to detect inhomogeneities in magnetization along the surface of a ferromagnetic substance. The same method somewhat refined and applied to single crystals has shown that instead of being homogeneously magnetized, as might have been expected, flux leaves or enters the surface in a regular way. For instance, a powder of magnetic iron oxide ($Fe_2O_3$) allowed to settle slowly out of suspension onto the surface of a nickel crystal, settles in a pattern such as that shown in Fig. 9. The larger periodicity is roughly 0.1 mm. These lines are not permanent structural features, but can be made to move by changing the magnetization. Similar, though characteristically different, results have been obtained for iron and cobalt crystals (F. Bitter, *Physical Review* v. 41, 1932, p. 507). How these patterns can be fitted into theories, or even what part they play in the process of magnetization, is at present a mystery.

# A Study of Nitrogen in Metallic Arc Weld Metal

ONE of the most important and most difficult problems involved in electric welding is the control of the nitrogen content in the deposited weld metal. For the most part, research work to date has been concentrated upon the *effect* of nitrogen in the deposited metal and not upon the actual *control* of the nitrogen content of the deposited metal.

In recognition of the importance of this subject, the A.I.E.E. board of directors, acting upon the

recommendation of the A.I.E.E. committee on electric welding, in 1932 enlisted the coöperation and support of The Engineering Foundation toward the underwriting of a research project then under consideration at Massachusetts Institute of Technology. With the Foundation's support, John W. Miller, a graduate of Simpson College (1929) and recipient of a masters degree from the M.I.T. mining and metallurgy department, initiated an extensive research into the subject of nitrogen in metallic arc weld metal. Upon completion of his work, Mr. Miller was awarded the degree of doctor of science. Doctor Miller's thesis has been bound by the A.I.E.E. and placed in the Engineering Societies Library, 29 West 39th Street, New York, N. Y., where it is available for reference purposes.

Doctor Miller's thesis embraces a comprehensive review of the literature, and other topics related to the subject of his research. With specific reference to the nitrogen content of deposited weld metal, Doctor Miller studied and reported the effect of the nitrogen content of the welding atmosphere, carbon content of the electrode, electrode size, amperage and voltage, lime coating on electrodes, hard drawn and annealed, electrodes, and reversed and straight polarity.

In his investigation Doctor Miller found that the nitrogen content of weld metal deposited by the metallic arc process may be diminished by increasing the size or diameter of the electrodes, increasing the carbon content of the electrode, increasing the current density, reversing the polarity, decreasing the nitrogen content of the arc atmosphere, decreasing the voltage used, and using heavily coated electrodes.

A rapid method for the determination of nitrogen in weld metal is outlined in detail and a discussion of the microstructures found in metallic arc weld metal is included.

The author proved, by means of X ray diffraction work and heat treatment, that the needles found in the weld metal probably are due to the presence of nitrogen in the form of the compound $Fe_4N$ which is precipitated and segregated. By the same means, he has shown that the main oxide present in weld metal is the magnetic oxide of iron. Also it was found that the needles may occur at both the grain boundaries and within the grain itself and that they may tend to segregate. The presence of Neumann bands was noted and some discussion given them.

The report shows that conditions leading to the absorption of nitrogen also lead to the burning out of carbon and contamination by oxygen.

A discussion of the gases probably responsible for blowholes in arc weld metal is included. It is explained that the gas most likely to form blowholes in the weld metal is carbon monoxide with perhaps the assistance of hydrogen and hydrocarbons (if such occur) which may be present.

Excellent evidence is shown that, at the high temperatures of welding, an increase in the temperature causes a decrease in the solubility of nitrogen in iron.

Physical test data show that conditions leading to a decreased nitrogen content result in improved physical properties.

# Electrical Practices in USSR Steel

**On the basis of several years of first hand association the author here describes some of the current electrical practices in the steel industry of the Soviet Union, and indicates the general trend of development.**

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THE GENERAL PROGRAM for the development of the steel industry of the Soviet Union includes some rehabilitation of old plants. To a large degree, however, it involves the construction of complete new plants or new departments. Projects for some 10 complete new plants may be considered as active. While these plants differ individually, in most cases they involve coke ovens, sintering plants, blast furnaces, steel works, and rolling mills, together with a large number of shops and accessory units.

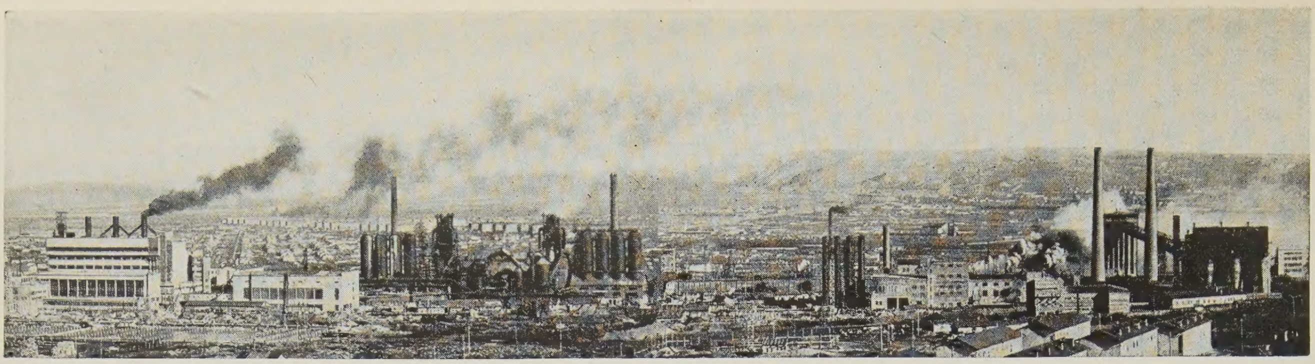
In most instances the steel plants do not stand alone. Brick plants, cement plants, car fabricating shops, etc., having industrial relationship with the steel plants, are located contiguously. Towns for the employees of these industrial districts also are involved.

In a nation where all industry is under the control of a central government, several advantages are possible, both in standardization of practices and in coördination of related enterprises. To some extent, such coördination has been applied in the utilization of energy sources and the provision of energy services to these districts. For instance, by-product gases from coke ovens and blast furnaces are used, not only in the steel works, but in the related plants and in the towns. District heating is, in some degree, associated with power development at the steel plant. Water supplies are sometimes coördinated.

In most cases those steel plant sites that are most favorable in other respects are not favored as to water supply. This perhaps is a principal reason that has dictated the general policy of restricting the size of electrical generating stations in the steel plants. These generating stations are sufficiently large to protect essential consumers, to utilize by-product fuels, to provide bled steam for district heating needs.

The initial steps toward rehabilitation of old

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*



**General view of the Kuznetsk steel plant, Stalinsk, Siberia, taken in 1932, showing the power house at the left, blast furnaces in the center, and coke oven plant at the right**

plants, under German influence, involved the installation of several gas engine driven generators. More recently this policy has been abandoned entirely in favor of turbine generators. A popular size of turbine generator in the larger plants is 25,000 kw, the station comprising 1 to 4 such units. Supplementary power, at these plants, is received from high voltage loop lines usually at 32 or 110 kv. These loops are parts of existing or proposed networks supplied from large and favorably located generating stations.

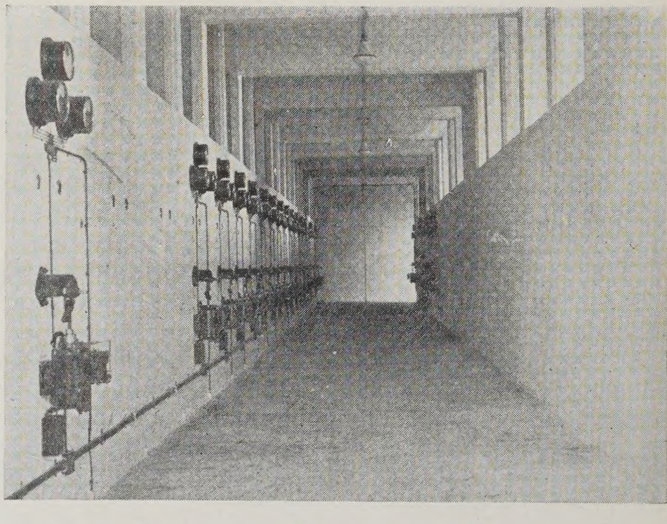
In the matter of power distribution, each plant, of course, is a study unto itself. A general arrangement that has proved advantageous in several cases involves an electrical generating station in conjunction with the blowing station at the blast furnaces. The step-down substation at which supplementary power is received is located in the general vicinity of the rolling mills. This arrangement is attractive because of the predominance of electric power consumption in the rolling mill area. The generating station and step-down substation are connected by tie lines.

Underground distribution of electric power strongly predominates. Greater expected reliability is the principal factor that dictates this practice.

In a few instances tunnels are provided for the underground cables. To a limited extent, particularly for small outlying consumers, armored cables of the parkway type are buried directly in the ground. Preference is growing rapidly, however, for the American system of duct line construction. Fiber duct is favored, but is available only by import. Initially, small sewer tile is being substituted. Cables are paper insulated. Varnished cambric insulation is not yet produced in the Soviet Union, but its manufacture at an early date is contemplated.

In general, new Russian steel plants cover considerably larger areas than would be required in America, and consequently the distribution of electricity and all other services is rendered somewhat more expensive by this condition. Track curves of large radius contribute to this situation, such curves being necessitated by the wide track gauge and by the 4-wheeled rigid-axle cars.

Two systems of primary distribution were carefully compared in connection with several projects. In one system power was to be generated and distributed at 6 kv. The larger motors were wound for this voltage; for smaller motors, 380 volts were used. In the other system power was to be generated at 10 kv. The larger motors were wound for that voltage; intermediate motors were wound for 3 kv, and the smallest motors were rated at 380 volts or, in some cases, at 500 volts. Each of these systems has advantages and disadvantages. Cost analyses indicated that the savings in first cost associated with the use of the 10-kv system were not great, and in general were insufficient to warrant the adoption of this higher voltage in the face of slightly reduced operating efficiencies with high voltage motors and increased extent of transformation. In exceptional cases where large power plants were involved or where transmission distances were extended, the use of 10 kv was thought to be justified. The practice therefore was adopted tentatively to design the windings of large main drive motors for delta connection at 6 kv, and star connection at 10 kv.



**Center aisle construction typical of Russian steel mill substations**

Protective relays and solenoid operating mechanisms are mounted directly on cell walls. Oil switches can be operated manually by means of removable handles, not shown. Servicing is done from outdoors through exterior doors in each cell

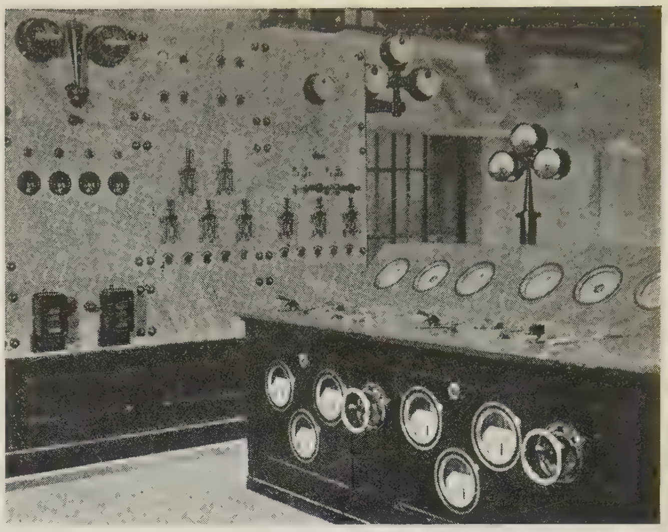
The frequency of 50 cycles is standard throughout the Soviet Union. This frequency is well adapted to steel plant requirements.

In general, it is considered preferable to ground the 10-kv and 6-kv systems through high resistance, in conformity with European practice. The 3-kv systems and 380-volt systems, of restricted extent, are generally ungrounded. Lighting systems are grounded.

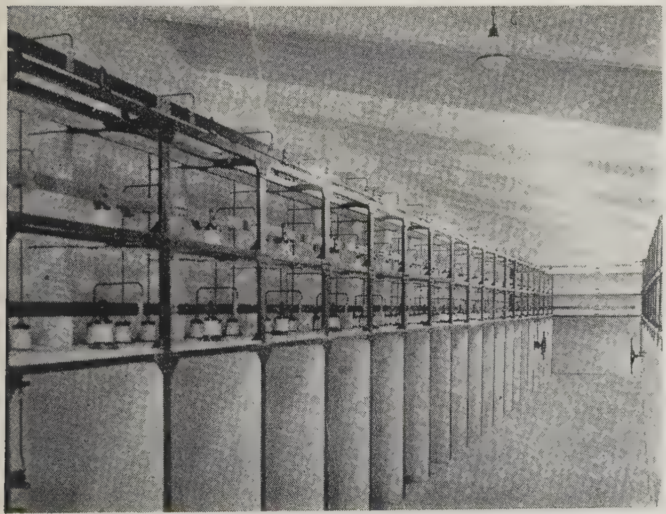
Although there are, of course, many variations to suit local conditions, distribution systems are commonly of radial or modified radial types. The Russian tendency was to provide duplicate radial feeders from the main distribution points direct to most consumer substations. This practice has been modified gradually in favor of 2-stage radial distribution in which lesser consumers are sometimes supplied as subfeeds from main consumer substations. The use of emergency tie lines between consumers, rather than duplicate radial feeders in certain instances, also is gaining headway. Loop systems of distribution were considered in several projects, but cost analyses generally were unfavorable. The limitations of Russian made relays now available also militate against this system. Loops therefore are used in relatively few instances.

Substation designs and switching arrangements savor strongly of continental European practice. The prevailing basic scheme is the double bus with 2 sets of disconnecting switches and one oil switch for each connection. The disconnecting switches are manually operated, and arranged to be closed either selectively or simultaneously; oil switches usually are remote electrically operated.

In general the substations are long, narrow buildings, having an operating aisle centrally located between 2 rows of switches. Oil switches are placed in small chambers adjacent to exterior walls, and exterior doors are provided for access to and removal of the equipment. Glass is provided either in or above these doors to serve as a relief valve for gases liberated in the oil switch chamber in the event of an oil switch explosion.



Control room in a Russian steel mill substation



Upper level of switch structure typical of Russian steel mill substations

6-kv buses appear above; disconnecting switches are in the lower compartments

The wide spread adoption of this general switching system and this mode of substation construction results in part from the fact that existing Russian types of oil switches and fittings were designed for and are adapted to such systems. These methods are not confined to the Russian steel industry, but characterize Russian electrical practice in general. American electrical engineers who have coöperated in designing Russian steel plants consistently have criticized and opposed these switching practices and have recommended the adoption of American practice which may very broadly be characterized as entailing:

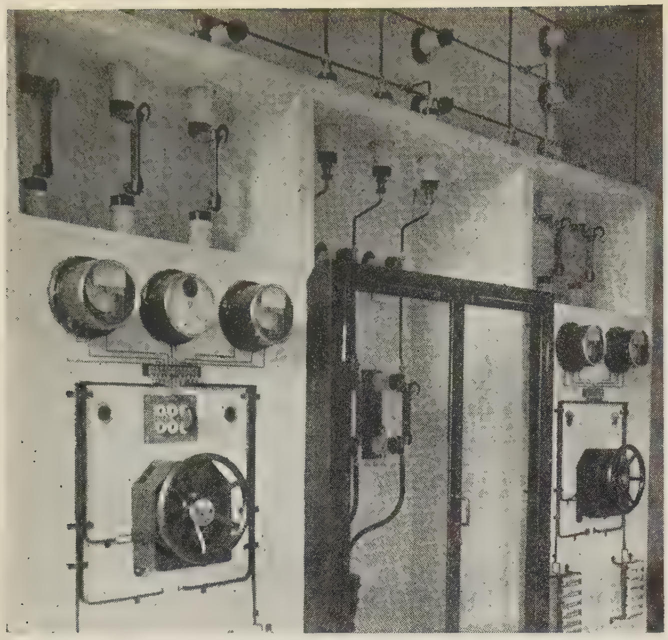
1. Double bus with 2 selective oil switches per circuit for important generation stations.

2. Single bus for nearly all substations, this bus being sectionalized to promote reliability and flexibility wherever the character of the station demands such sectionalization.

Probably no phase of electrical practice in the Russian steel industry is less advanced than the field of switching and substation design. Three types of Russian made oil switches are available for steel plant use, having rupturing capacities of 250,000, 150,000, and 100,000 kva at 6 kv. Oil blast or deion features have not yet been applied to any of these switches.

Since most of the Russian steel plants are connected to high voltage networks that are expected ultimately to involve large amounts of power, oil switches of rather high rupturing capacity would be indicated. Rather liberal use of reactors has been adopted for the double purpose of limiting short circuit currents and oil switch sizes, and for restricting voltage disturbances. These commonly take the form of feeder reactors. By this means the wide adoption of the 150,000-kva oil switch, an economical selection, has been made possible.

As yet, the use of cubicle and metal clad types of switching are hardly feasible in Russian steel plants except in connection with imported apparatus.



**Switching for 6-kv lighting distribution**

This view shows incoming feeder and manually operated primary oil switches controlling 2 3-phase transformers

As there is a shortage of rolled steel, and as the Russian electrical factories are unable as yet to meet all demands for equipment, it is hardly feasible to push the "factory built" idea. It is more feasible to erect masonry cell structures in the field.

The great majority of transformers used in Russian steel plants are 3-phase units. Only in the very large sizes is the use of single phase transformers resorted to. The Russians have been reluctant to locate transformers in steel plants out of doors. The practice of housing transformers in ventilated rooms or chambers still prevails, although a few outdoor installations have been projected. Most of the transformers are of oil-insulated self-cooled types. Bouchal's type of temperature relays are adopted frequently, this being inherited practice.

For supplying direct current to main roll drives, motor generators are standard. For supplying direct current to auxiliary drives, motor generators also are used. Existing Russian sets are of slow speed and rather cumbersome, expensive, and limited in commutating ability. Mercury vapor rectifiers, produced in the Soviet Union, are favored by many, and are being tried out in a few plants. If they prove satisfactory, their wider adoption seems likely.

Main roll drives will be of 3 principal types, namely: reversing drives, constant speed drives, and adjustable speed drives. The Russian factories are just starting to build main roll drives. It is probable that, for some time to come, most main roll drives will be imported. Russian designs in all probability, will follow American practice rather closely. Two 7,000-hp reversing motors for driving blooming mills have been built in the Soviet Union, the control being along American lines. The use of synchronous motors for Ilgner sets for reversing drives for rail, structural, and universal mills is seriously considered. It is probable that nearly all constant speed drives will employ synchronous motors. The general tendency will be toward highly subdivided groups with one motor driving 1, 2, or 3 stands. Self-contained parallel-shaft gear units are favored over bevel gears and lay shafts. As yet the Russians display a desire to restrict gearing to rather low ratios.

For adjustable-speed drives for new mills the direct-current motor will be almost universally employed. For these motors 600 volts has been adopted as standard, and Ward-Leonard starting will be usual. Individual drives will be the rule rather than the exception. For auxiliary drives and cranes the use of direct current at 220 volts has been widely adopted for new plants. Some of the older plants retain a-c auxiliaries; others use direct current at about 500 volts. The latter 2 systems represent prevalent European practice.

The Russians have adapted for mill and crane use a "box" type of crane motor, the armature of which is removable through the end of the frame. Steps are being taken to split horizontally the frames of some of the larger sizes. This motor has an armature of rather large diameter and considerable inertia. It is built only in the "bare" type without axle bearings. This motor was adopted as a necessary expedient due to its availability, many Russian engineers realizing its deficiencies. The development of a mill-type motor along American lines is a probable occurrence of the near future.

Inherited designs of Russian controllers are largely of the drum type. The advantages of magnetic control are fully recognized. Russian factories have produced several magnetic controllers designed along American lines. The wide spread use of this type of control is limited only by lack of availability.

New Russian steel plants are designed for rather high illumination intensities. In accord with customary European practice, initial installations are being made on the basis of 220-volt lamps, and 3-phase distribution. This system was adopted because of stringency of copper, although there is a division of thought, many Russian engineers favoring the use of 120-volt lamps. The use of single phase circuits for lighting has been prevented in part by the fact that Russian electrical factories do not as yet produce small single phase distribution transformers. The practice of supplying separate transformers for lighting supply recently has been adopted. In some of the earlier installations a combination 220/380-volt supply for power and lighting was used.

It is anticipated that alloy steels will find considerable demand in the Soviet Union. The production of alloy steels in electric furnaces will be restricted, however, by the high cost of electric power at most steel plant sites. The situation at Dneiprostal (Zaporosche) plant is exceptional. This plant is located on the Dnieper River contiguous to the Dneiprostroy hydroelectric development. Several electric furnaces have been installed there for production of alloy steels. Ferro-alloys will also be produced there in large electric furnaces. Some

of these furnaces will consume marginal power that is not available throughout the entire year.

It should not be considered that the electrical practices sketchily outlined in the preceding paragraphs represent final, fixed procedure in the steel plants of the Soviet Union; the whole situation is in a state of flux. Systems are evolving slowly. To a large extent, usage has been dictated by characteristics of equipment available from Russian electrical factories or by import from sources affording attractive commercial terms. To no small degree engineering has been compromised to necessity.

A consistent and well advised attempt is being made to crystallize and standardize practices as the industry develops. The commission which functions to this end is one which comprises representatives of GIPROMEZ, the general planning institute for the steel industry, and V. E. O., the state electrical trust. As American engineers have been attached to both of these organizations, the earmarks of American practice are seen in many directions.

# A New Laboratory for High Voltage Testing

**A description of the impulse, power frequency, and high frequency testing facilities now available in a new high voltage laboratory is given in this paper. In particular, a new form of 3,000-kv impulse generator is described wherein size, inductance, and stray capacitance have been reduced to a minimum by a helical arrangement of capacitor units.**

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IN ORDER THAT present day line insulation problems may be studied fully in the laboratory, it is desirable that the proper voltage generating, measuring, and recording facilities be available. To investigate the lightning insulation necessary for operating voltages up to the present limit of 287 kv, an impulse generator for voltages of the order of 3,000 kv is essential. To take care of normal frequency requirements over the same range, a 60-cycle voltage of at least 1,500 kv to ground is desirable. For special high frequency studies an oscillator having a generating capacity of about 750 kv will suffice.

Although indoor testing with the above facilities affords freedom from unfavorable weather conditions, the need for ample electrical clearances, particularly for full-sized tower and equipment set-ups, dictates that some provision for outdoor studies be made. It was with this in mind that the new laboratory arrangement described herein was planned. In Fig. 1 is shown a plan of the laboratory building and grounds. The main laboratory building is shown at the left, and to the right is the outdoor test area. Here the various tower structures are stored, each mounted on its own car and located on the proper storage track. In this way any structure may be brought to the test track shown, where it is easily accessible for impulse tests up to 3,000 kv to ground and 60-cycle tests up to 2,000 kv to ground. For these tests connection is made either to the portable impulse generator at one end of the building or to the chain connected transformer set at the other, the latter having 2 units outdoors and 1 indoors. In the arrangement shown on the test track in Fig. 1, a single-circuit steel tower insulation assembly is connected in parallel with a wood pole H-frame assembly for a simultaneous impulse flashover test on both to determine the relative insulating properties of the 2 under lightning.

In Fig. 2 is shown a perspective view of the interior of the main laboratory building. The impulse generator, which will be described fully in the following paragraphs, is at the left with the 2,000-kv section connected for test. The 1,000-kv top section is suspended above the door, only the lower insulators of it being visible. On the right is the power frequency test area. The transformer mounted on the porcelain pier in the pit is the first unit of the 2,000-kv chain-connected set and the smaller unit in the corner is for special power frequency tests up

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted May 31, 1934; released for publication July 20. 1934. *Not published in pamphlet form.*

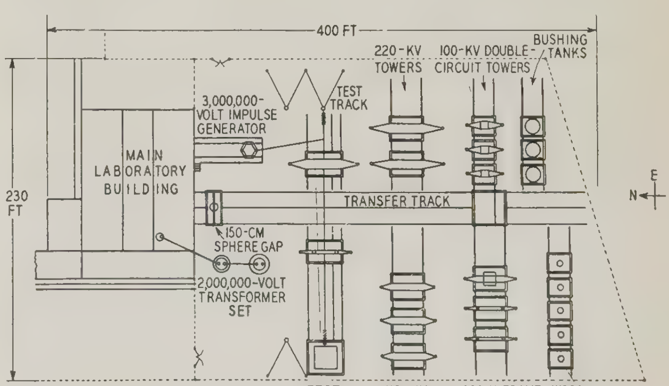


**Fig. 1. Laboratory building and outdoor test area**

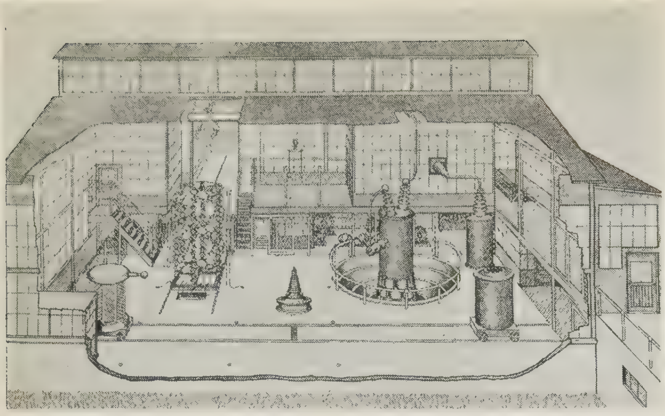

Fig. 2. Interior of main laboratory building

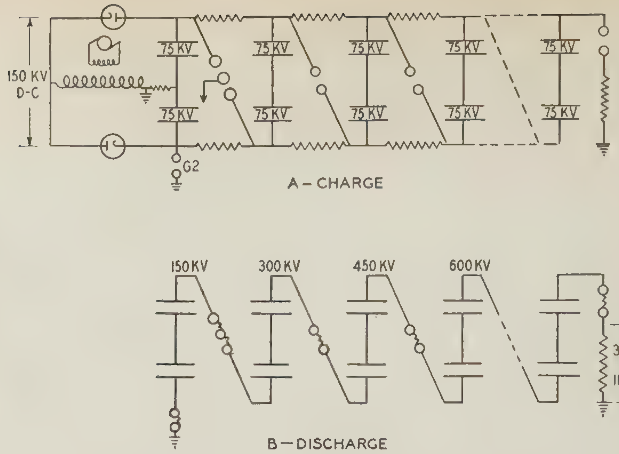


Fig. 3. Circuit of impulse generator

to 300 kv. Mounted on the tracks in the left foreground is the air-insulated transformer coil for high frequency testing. The equipment and rooms in the background are for special test purposes to be described later. The mezzanine platform in the center background provides a safe vantage point for witnessing practically all tests, both indoor and outdoor.

Impulse Generating Facilities

While an upper limit of 3,000 kv was desirable for the high insulation range, it was decided that 2,000 kv would take care of most requirements and therefore would suffice for the indoor installation. Accordingly, a portable impulse generator for 2,000 kv was designed, to which a 1,000-kv section could be added for operation outdoors. As the Marx circuit of parallel charging and series discharging was adapted ideally to such an arrangement, it was chosen for the generator. The particular form used is shown in Fig. 3, which illustrates the parallel charging stage and the series discharging stage. At the completion of the charging stage the 3-electrode gap, $G_1$, is sparked over by a control circuit surge placed on the middle electrode. This causes all the remaining gaps to sparkover successively, thereby connecting all capacitor units in series as shown in the discharge diagram. Capacitor units each rated 75 kv and 0.33 $\mu$f are used, with 2 in series in each bank as shown. There are 42 such units in the set so that a maximum charge voltage of about 3,150 kv may be obtained.

The arrangement of the charging transformer circuit is somewhat different from that used in most Marx generators. Instead of having one of the transformer terminals connected to the midpoint of the first capacitor bank as is often done, this terminal is grounded and a resistance is inserted between this ground point and the capacitor bank midpoint, as shown in Fig. 3*a*. In this way one transformer terminal is always kept at ground potential instead of at a voltage above ground equal to that of one capacitor unit, which latter imposes on the other terminal a potential to ground of twice this voltage. This greatly relieves the stresses to ground of the transformer winding and permits a transformer of lower voltage insulation to be used. The gap $G_2$ therefore must be inserted below the first bank in order to bring that point to ground potential upon discharge. Another advantage of this arrangement is that it always permits tripping the impulse generator by surging the middle sphere of the 3-electrode control gap with a negative impulse from the oscillograph cathode circuit regardless of the polarity of the main surge. This follows since both outside spheres of the 3-electrode gap are always at a potential from ground of opposite polarity during the charging period instead of one being grounded, as is the case when gap $G_2$ is omitted and the first capacitor bank is connected to ground.

It is apparent from Fig. 3*b* that during the discharge each successive capacitor unit position from left to right assumes an increasingly higher impulse

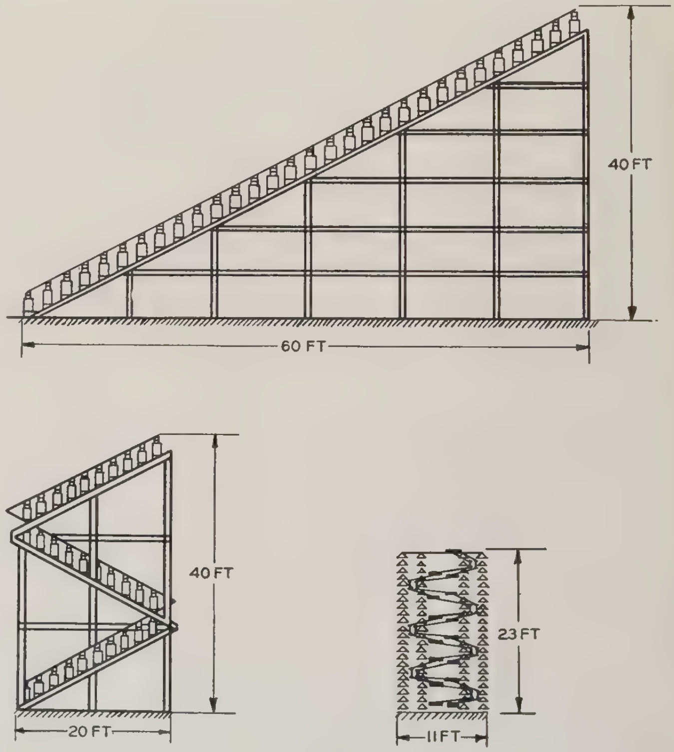


**Fig. 4. Forms of 3,000-kv impulse generator supports**

Top, triangular; below, zigzag and helical

voltage above ground, and must be insulated for it. In considering the insulating support for this purpose, it was necessary to remember that the complete generator had to be portable and capable of use outdoors. In order to have it portable, it was desirable that it be as compact and mechanically stable as possible. To allow outdoor operation, it was essential that no insulating material be used in the support which would be affected by moisture and therefore incur burning and charring internally or on the surface during voltage stresses. This last requirement precluded the use of wood, paper, molded compounds and the like, and made it practically necessary to adopt porcelain throughout.

In view of all of the above requirements, a generator support was developed wherein the capacitor units were arranged in an ascending helical path, supported by a hexagonal framework of pillar insulators of standard assembly. In this form all of the capacitor units could be mounted on their sides with their bushing terminals turned inward. This horizontal mounting of units resulted in an appreciable saving in height of structure, and reduced the lengths of leads between units and thereby the total inductance of the set. The use of a helical path kept the horizontal cross section of the generator at a minimum, thereby reducing the stray capacitance to ground and increasing the efficiency of the set both in regard to effective testing voltage and freedom from oscillations.

A comparison of the size of the helical mounting and the familiar triangular and zigzag mountings often used is shown in Fig. 4. Typical dimensions of the latter 2 mountings have been chosen for a 3,000-kv set and are found to be appreciably greater than the helical form developed here. The complete 3,000-kv helical set on its motor driven car just outside the laboratory door may be seen in Fig. 5. In Fig. 6 the set has been moved into the building for tests up to 2,000 kv, the 1,000-kv top section now being suspended in the background just inside the door.

The helical arrangement of capacitor units, all mounted horizontally with terminals inward, provides a ready means for controlling simultaneously the spacings of the series spark gaps. To do this, one sphere electrode of each gap is fitted to a radial porcelain rod which can be moved longitudinally through connection to a rotating center stack of pillar insulators. A close-up view (Fig. 7) of the internal structure of the generator illustrates this feature. The rotation of the pillar stack and the consequent adjustment of all gap settings, including the 3-electrode gap, is controlled electrically from the oscillograph room, thereby allowing the entire operation of the set over the whole voltage range to be handled from that point. The circuits for surging the oscillograph cathode and 3-electrode gap, for operating the alarm bell, and for synchronizing with power frequency voltages are actuated by motor driven contactors. By this means successive surges on a test occur automatically so that the operator is free to observe and photograph all cathode ray oscillograph records.

The radial supporting tubes just described for the series spheres, as well as all the charging resistance holders, were made of porcelain in line with the plan of having no insulating material on the generator which could not operate under outdoor conditions.

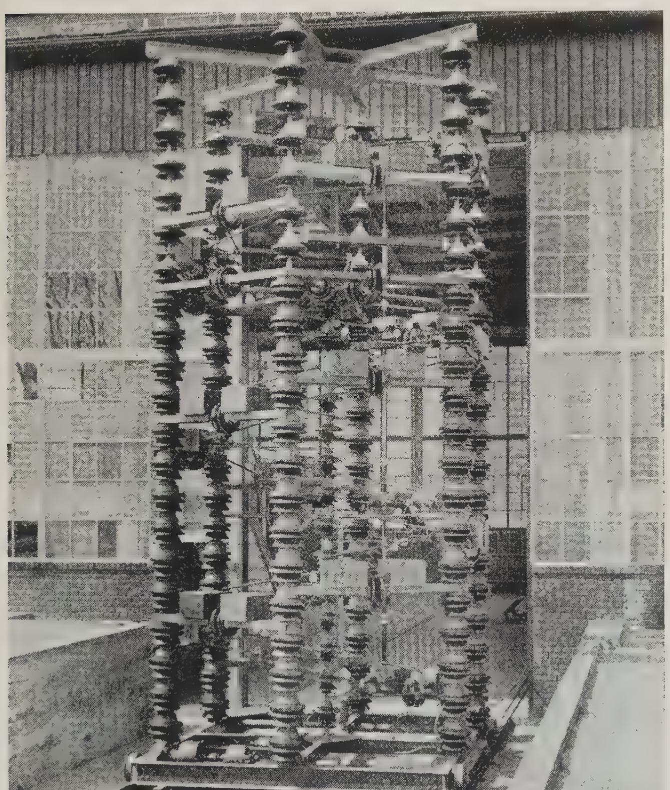

Fig. 5. Complete 3,000-kv impulse generator

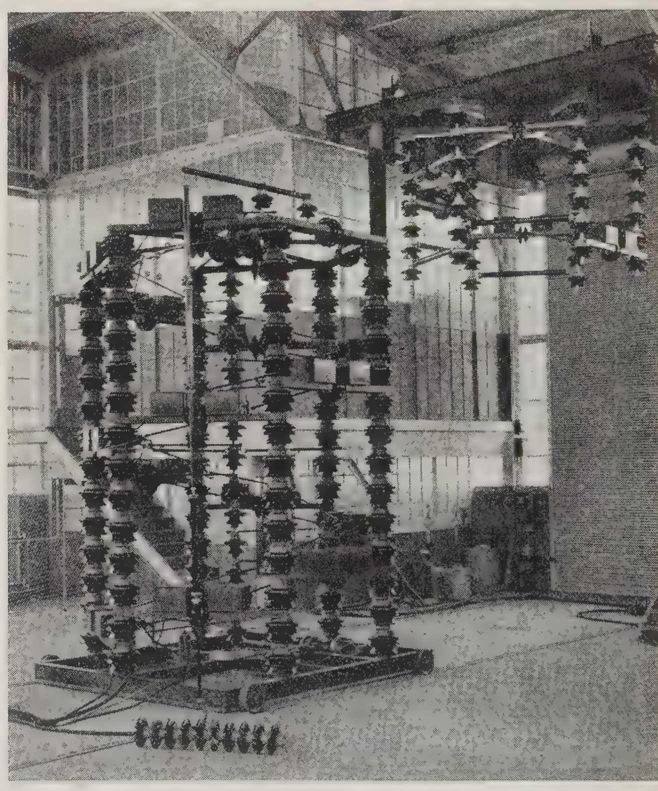

Fig. 6. Impulse generator with upper section removed

The inherent constants of the 2,000-kv section are:

| | |
|---|---|
| Series capacitance | 0.0118 $\mu$f |
| Series inductance | 52 $\mu$h |
| Series resistance (minimum for complete damping) | 600 ohms |

The calculated value of 600 ohms necessary to effect complete damping of the oscillations due to the inductance and stray capacitance of the circuit produces a wave front of about 1 $\mu$sec when no other capacitance is connected in the test circuit.

In Fig. 8 are shown typical cathode ray oscillograms taken with the 2,000- and 3,000-kv sections. The usual resistance type of voltage divider was used for these, a high voltage cable being connected from the lower end of the resistance column to a grounding resistor equal to the cable surge impedance at the oscillograph. The voltage wave across certain taps of the latter resistor was then applied to the oscillograph plates for recording. The voltage divider itself consists of 4,000-ohm units, each made with non-inductively wound wire and mounted in oil filled light porcelain tubes of oval cross section. These resistors may be seen suspended near the center of the 2,000-kv set in Fig. 6. The oscillograph room, which is completely enclosed by metal for shielding purposes, may be seen in Fig. 2 at the right of the impulse generator.

The inherently low series inductance of the generator circuit affords a ready means for securing com-

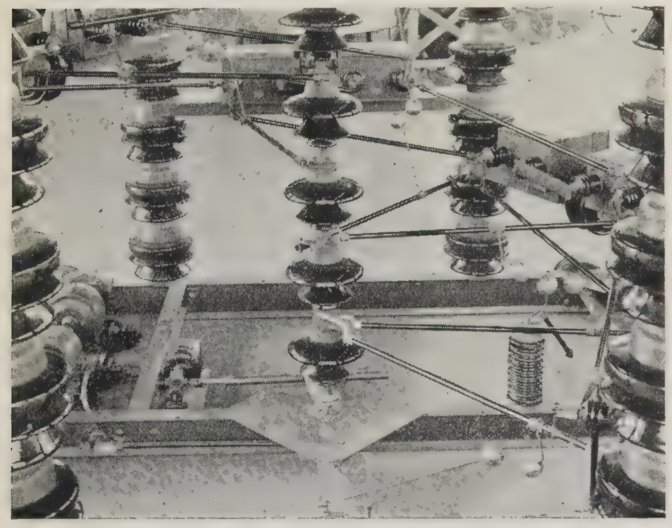

Fig. 7. Structure of impulse generator

paratively high impulse surge currents. Although no high current studies have been made as yet, preliminary calculations and tests indicate that 40-$\mu$sec surges of over 100,000 amp at 150 kv may be obtained.

## Power Frequency Testing Facilities

As noted previously, power frequency tests up to approximately 2,000 kv to ground may be made by means of a 3-unit set of 700-kv transformers arranged for chain connection. Each transformer is of the shell type with the center of the high voltage winding connected to the core and tank. Accordingly, each tank had to be insulated from ground to allow full unit voltage to ground to be developed. To allow for outdoor operation, this insulating mounting was made from special porcelain tile. The tile pier supporting the indoor unit, shown at the right in Fig. 2, and the tank clearances to ground have sufficient insulating properties to permit this

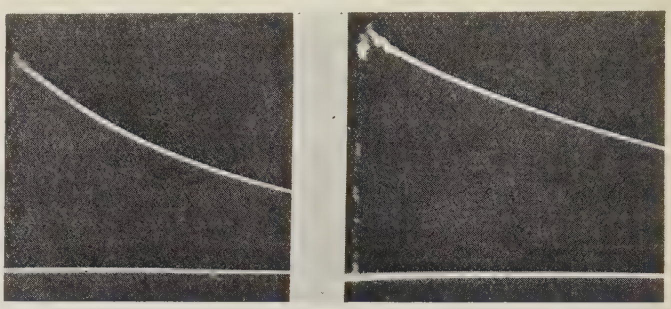

Fig. 8. Oscillograms of impulse generator voltage waves

(Left) $1^1/_2$x40-$\mu$sec wave of lower section charged to 2,000 kv

(Right) 40-$\mu$sec wave of complete 3,000-kv generator without series damping resistance, showing low amplitude of oscillations; charge voltage, 2,800 kv

unit to be excited by one of the outdoor units so that a power frequency testing voltage of more than 1,000 kv to ground may be secured indoors. With this unit operating as the ground transformer and exciting the 2 outdoor units, potentials up to 2,000 kv to ground may be obtained. Obviously, the outdoor units must have their tanks insulated by the porcelain piers for voltages of the order of 1,050 kv and 1,750 kv to ground, respectively. The availability of these 3 identical units affords facilities for making 3-phase tests up to approximately 1,200 kv between lines. Generator facilities are available for making the above tests at 25 and 50 cycles as well as at 60 cycles, although the reduced frequencies obviously lower the voltage ranges available for tests, due to the saturation limits of the connected transformers.

On the right mezzanine section of Fig. 2 is located a special room for corona and radio influence tests. It is entirely enclosed with sheet metal to shield radio studies from outside influence, and may be completely darkened for corona observations on insulators. Another room, associated with the laboratory but separated from it to avoid contamination, is available for making special fog, dust, and smoke studies on insulators. Facilities are available here for observing and recording all insulator discharges associated with atmospheric contamination conditions.

For special high-current power-frequency tests on busbars, bushing leads, etc., generator facilities are present from which sustained currents of over 5,000 amp may be secured.

### High Frequency Testing Facilities

For special insulation studies, a high frequency oscillator is available which is capable of generating wave trains of frequencies of from 50,000 to 100,000 cycles at potentials up to 750 kv. The air core transformer is shown mounted on a car at the left in Fig. 1 by which it may be moved to the proper test area for the necessary voltage clearances. The same transformer is used for studies, principally on radio insulators, at continuous wave frequencies up to 100,000 cycles. The generating source here is a Poulsen arc set.

# Output Wave Shape of Controlled Rectifiers

**Methods of estimating the harmonics in the output voltage wave of controlled voltage mercury arc rectifiers are given in this paper. Two limiting conditions are considered: one where the d-c circuit is sufficiently inductive to give substantially a smooth direct current, and the other where the d-c circuit is noninductive. Formulas for the harmonics when the rectifier is delivering load are presented, and curves are given that make it possible to calculate readily the lower orders of these harmonics which appear in the output voltage of 6- and 12-phase rectifiers.**

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MERCURY ARC RECTIFIERS when equipped with grids may be given output voltage characteristics very similar to those of a d-c generator. Output voltages ranging from zero to the voltage the rectifier would develop when not equipped with grids may be obtained by shifting the phase of the grid excitation in the proper manner. Unlike the d-c generator, the harmonics present in the output voltage wave are inherent in the normal operation of the device. The purpose of this paper is to discuss the output voltage wave shape of mercury arc rectifiers equipped with grids to control the output voltage under various operating conditions, and to give methods for estimating the wave shape of this voltage in any given case.

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### Operation of Control Grids

The grid excitation of the rectifiers to be studied is such that the grids cannot stop, decrease, or modulate current flow from the rectifier anode, once this current flow has started. When properly excited, the grids can retard the point at which current flow from the anode starts, thus reducing the portion of the positive half cycle of anode voltage that is effective in producing output voltage. It will be assumed that current flow from the anode will start at the instant the excitation for the grid working with that particular anode changes from negative to positive, providing the excitation of the anode is such as to allow current flow from the anode to start at that particular instant.

In Fig. 1 is shown the output voltage wave shape of a controlled voltage rectifier at no load, with the anode firing period retarded by an amount $\alpha$. The grid excitation for the working anode changes from negative to positive at point $B$, thus allowing anode $b$, the potential of which already is suitable for allowing the flow of current, to start firing. The output voltage wave shape under load is shown in Fig. 2. Commutation between anodes $a$ and $b$ starts at point $B$ and continues until the current from anode $a$ becomes zero at point $C$.

In analyzing the wave shapes of ordinary 6- and 12-phase rectifiers it has been found that the assumption of a steady direct current gives sufficient accuracy for practical purposes. The usual types of load generally have enough inductance to give a fairly smooth current. When grid control is used and the range of voltage control is not large, for instance 10 per cent, reasonably accurate results will be obtained if a steady direct current is assumed. For a wide range of voltage control the voltage curve at the lower limit deviates considerably from the average, and therefore the current may not be smooth unless the load is highly inductive. Therefore, 2 limiting conditions are considered in this paper: highly inductive loads in which the current wave shape closely approximates that of a perfectly smooth direct current, and noninductive loads in which the current is pulsating and has the same wave shape as the load voltage. When necessary the voltage wave shape can be estimated for the 2 limiting conditions and the wave shape for actual conditions can be determined by interpolation.

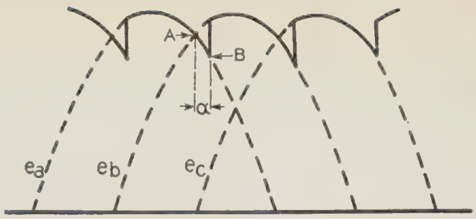
### Theoretical Wave Shape of a Rectifier Supplying a Highly Inductive Load

The output voltage of the ordinary rectifier has been analyzed by several authors.[1,2] By analyzing the voltage wave of Fig. 2 in a similar manner a

1. For references see list at end of paper.

Fig. 1. Output voltage wave shape of controlled voltage rectifier at no load

$\alpha$ = angle of retard




Fourier series is obtained in which the coefficients of the sine and cosine terms for the harmonics of the order $mp'$ are, respectively,

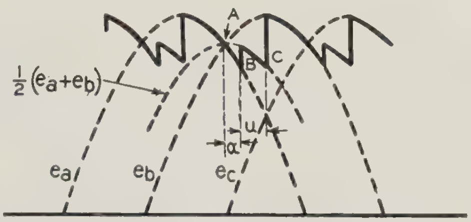
$$a_m = \frac{E_{do}}{2}\cos m\pi\left[\frac{\sin(mp'+1)(u+\alpha)+\sin(mp'+1)\alpha}{mp'+1} - \frac{\sin(mp'-1)(u+\alpha)+\sin(mp'-1)\alpha}{mp'-1}\right] \quad (1)$$

$$b_m = \frac{E_{do}}{2}\cos m\pi\left[\frac{\cos(mp'+1)(u+\alpha)+\cos(mp'+1)\alpha}{mp'+1} - \frac{\cos(mp'-1)(u+\alpha)+\cos(mp'-1)\alpha}{mp'-1}\right] \quad (2)$$

Fig. 2. Output voltage wave shape of controlled voltage rectifier under load

$\alpha$ = angle of retard

$u$ = angle of overlap




The rms value of the harmonic of order $mp'$ is given by the formula

$$h_m = \frac{1}{\sqrt{2}}\sqrt{a_m^2 + b_m^2}$$

The phases of the harmonic voltages referred to the maximum point of the applied voltage can be obtained from eqs 1 and 2.

In these formulas

$E_{do}$ = output voltage at no load with no retard
$p'$ = number of secondary phases
$u$ = angle of overlap
$\alpha$ = angle of retard of anode firing period
$m$ = 1, 2, 3, 4, . . . etc.

It may be noted that the magnitudes of the harmonics depend upon the angle of overlap $u$, and the angle of retard $\alpha$. The angle of overlap without grid control is given by the following formula which has been published before:[1, 2, 3]

$$u = \cos^{-1}\left(1 - \frac{IX}{E_0 \sin\frac{\pi}{p}}\right) \quad (3)$$

where

$u$ = angle of overlap
$I$ = load current in each group of transformer secondary windings
$E_0$ = peak value of voltage to neutral on the secondary side of the transformer
$X$ = reactance of the circuit in which commutation takes place
$p$ = number of phases in each group of transformer secondary windings; $p$ = 3 for the 6-phase double-Y and 12-phase quadruple-Y connections; 6 for the 6-phase star, 6-phase forked, and 12-phase in double-6-phase relation; and 12 for the 12-phase star connection

Equation 3 has been extended to cover the case of rectifiers with grid control[4] and becomes

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{IX}{E_0\sin\frac{\pi}{p}}\right)\right] - \alpha \quad (4)$$

where all symbols are as defined previously.

The output voltage with load and with retard of the anode firing period is

$$E_d = \frac{E_{do}}{2}(\cos\alpha + \cos(\alpha + u)) \quad (5)$$

where $E_d$ is the output voltage with load, and $E_{do}$ is the output voltage at no load and with no retard; $E_{do}$ can be calculated from the following formula:

$$E_{do} = \frac{E_0 p}{\pi}\sin\frac{\pi}{p} \quad (6)$$

By substituting in eq 5 the value of $u$ given by eq 4 the following expression is obtained for the output voltage with load in terms of angle of retard:

$$E_d = \frac{E_{do}}{2}\left(2\cos\alpha - \frac{IX}{E_0\sin\frac{\pi}{p}}\right) \quad (7)$$

Equations 5 and 7 allow for the effects of retard and overlapping, but do not allow for arc drop or the resistance drop resulting from losses in the transformer windings.

When the circuit constants, the voltage applied to the rectifier, the load, and the desired output voltage to be obtained with grid control are known, the angle of retard $\alpha$ and the angle of overlap $u$ can be calculated by eqs 4 and 7. Using these values the magnitudes of the harmonics can be estimated by eqs 1 and 2. Curves that simplify the calculations for several common types of rectifiers have been plotted from these equations. In preparing these curves the ratio of the controlled output voltage to the voltage the rectifier would develop at the same load without grid control has been used. The latter voltage is obtained by putting $\alpha = 0$ in eq 7. This

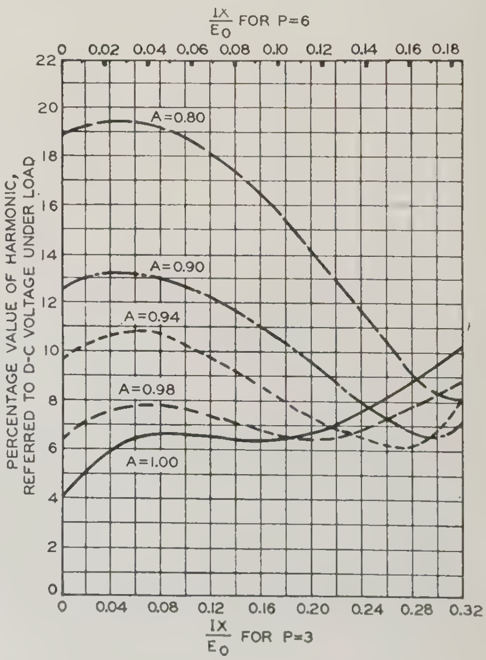



Fig. 3. The 6th harmonic in the output voltage of a controlled voltage rectifier as a function of IX/E0, for different values of voltage control ratio A

ratio, called the *voltage control ratio* in this paper, is represented by the letter $A$ and is given by the formula

$$A = \frac{2 \sin \frac{\pi}{p} \cos \alpha - \frac{IX}{E_0}}{2 \sin \frac{\pi}{p} - \frac{IX}{E_0}}$$

If for a given load the output voltage is reduced 10 per cent by grid control, the voltage control ratio is 0.90. Percentage values of the 6th harmonic plotted against $IX/E_0$ (for $p = 3$) for different values of voltage control ratio are given in Fig. 3. Similar sets of curves for the 12th, 18th, and 24th harmonics are given in Figs. 4, 5, and 6. The use of these curves in connection with 6- and 12-phase rectifiers will be discussed later in this paper. If the output voltage is given as a percentage of the no-load voltage with no retard, the voltage control ratio $A$ may be found by referring to Fig. 7 provided the conditions are those to which the curves of Figs. 3 to 6 apply. In order to make the curves of Figs. 3 to 7, inclusive, applicable to a wider variety of connections, a scale is given on the upper part of each figure showing values of $IX/E_0$ for $p = 6$. This scale is to be used for the connection to which this value of $p$ applies.

It is not necessary to calculate either the angle of overlap $u$ or the angle of retard $\alpha$ in order to estimate the harmonics from the curves of Figs. 3 to 6. In some instances it may be desired to know the values of $u$ and $\alpha$, and the curves of Fig. 8 have been prepared for that purpose.

The harmonics present on the output side of a 6-phase rectifier are the 6th, 12th, 18th, 24th, etc., harmonics of the supply system frequency. The percentage values of these harmonics are given by the curves of Figs. 3 to 6, inclusive. The use of the curves is illustrated by the following numerical example: A 6-phase rectifier is carrying a direct current of 800 amp and the output voltage is reduced 10 per cent by grid control. The transformer secondary windings are connected double Y, 6 phase. The commutating reactance of the transformer is 0.16 ohm and the equivalent reactance of the supply system for the commutating current is 0.01 ohm,[5] making a total reactance of 0.17 ohm for the circuit in which commutation takes place. The secondary voltage from anode to neutral is 540 volts (rms); then $E_0 = 765$ volts (peak). Since there are 2 groups, $I = 400$ amp. Then

$$\frac{IX}{E_0} = \frac{400 \times 0.17}{765} = 0.089$$

The voltage control ratio $A$ is 0.90. The percentage values of harmonics are read from Figs. 3 to 6 corresponding to 0.089 on the lower scale, since $p = 3$ for this connection, and using the curve $A = 0.90$. The values obtained are

| | |
|---|---|
| 6th harmonic | 12.8 per cent |
| 12th harmonic | 2.8 per cent |
| 18th harmonic | 0.7 per cent |
| 24th harmonic | 2.7 per cent |

In the 12-phase rectifier the 12th, 24th, etc., harmonics of the supply system frequency are present. The percentage values of these harmonics are the same as in the 6-phase rectifier and can be obtained from the curves. The 6th, 18th, and other odd multiples of the 6th harmonic are theoretically zero, but actually they are present in small amounts for various reasons such as the presence of harmonics in the supply voltage and unequal division of load between 2 groups of 6 phases. In tests on several 12-phase rectifiers without grid control[1] it was found that the average reduction in the 6th and 18th harmonics obtained by the use of the 12-phase connection is approximately 4 to 1 compared with the values that would be obtained with a 6-phase connection.

When harmonics are present in the supply voltage the output voltage wave shape is modified. It has

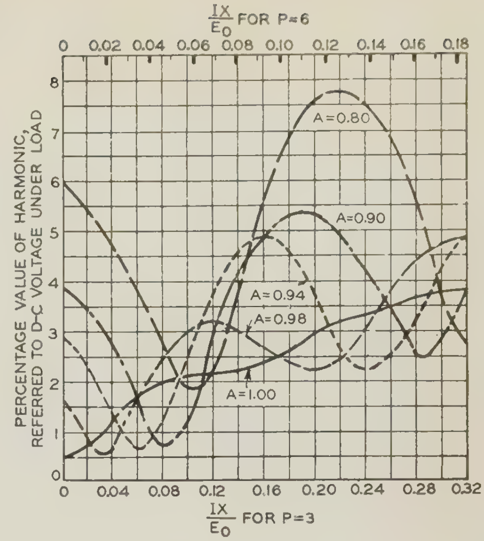



Fig. 5. The 18th harmonic in the output voltage of a controlled voltage rectifier as a function of $IX/E_0$, for different values of voltage control ratio A

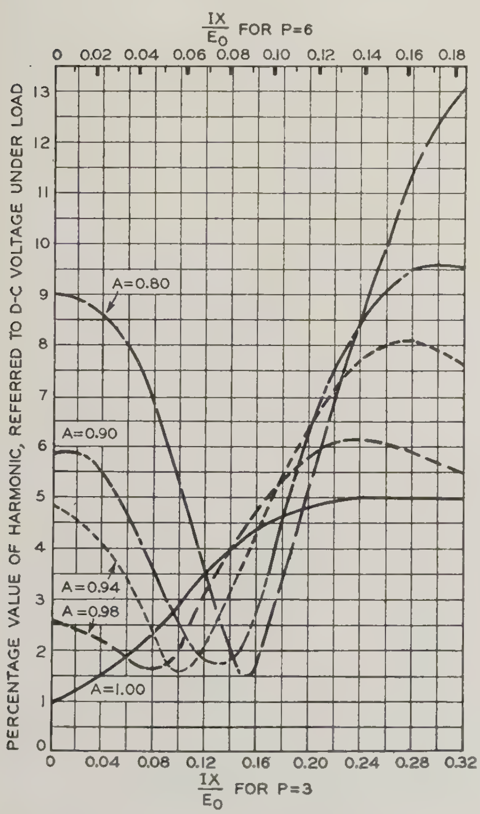



Fig. 4. The 12th harmonic in the output voltage of a controlled voltage rectifier as a function of $IX/E_0$, for different values of voltage control ratio A

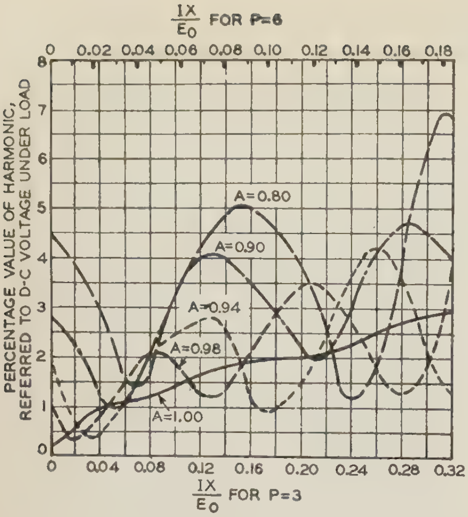
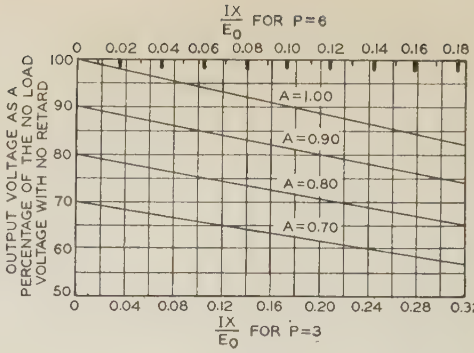



Fig. 6 (left). The 24th harmonic in the output voltage of a controlled voltage rectifier as a function of $IX/E_0$, for different values of voltage control ratio A

Fig. 7 (right). Output voltage as a percentage of no-load voltage with no retard plotted as a function of $IX/E_0$, for different values of voltage control ratio A




been shown[1] that in either the 6-phase or the 12-phase rectifier without grid control a 5th or a 7th harmonic voltage gives rise principally to a 6th harmonic voltage. Similarly, an 11th or a 13th harmonic produces principally a 12th harmonic; a 17th or a 19th harmonic produces principally an 18th harmonic, etc. In all these cases the percentage value of the harmonic voltages produced on the d-c side is approximately the same as the percentage value of the harmonic voltage on the a-c side which produces it. In the 6-phase rectifier with grid control the voltage curve is repeated at intervals of $^1/_6$ of a period of the supply voltage, as in rectifiers without grid control, and therefore harmonic voltages on the a-c side go through to the d-c side in the same manner. Similar considerations apply to the 12-phase rectifier with grid control. If the magnitudes and phases are known, the harmonic voltages resulting from harmonics on the a-c side can be combined with the harmonic voltages on the d-c side that arise in the normal operation of grid controlled rectifiers. If only the magnitudes are known the maximum and minimum values that may be expected can be estimated.

## Wave Shape of Theoretical No-Load Voltage With a Wide Range of Voltage Control

Referring to Fig. 1, which shows the output voltage wave of a grid controlled rectifier at no load, it may be noted that the voltage of phase $a$ is cut off at point $B$; and if the angle of retard $\alpha$ is increased, point $B$ is moved to the right along the curve $e_a$. If angle $\alpha$ is large enough point $B$ will be on the negative side of the zero line and the voltage curve will have negative loops. Such a condition would be approached at light load when the output circuit is highly inductive. Negative loops then would be obtained in the output voltage of a 6-phase rectifier when the angle of retard is more than 60 deg and in a 12-phase rectifier when the angle of retard is more than 75 deg. The average voltage is zero for both rectifiers when the angle of retard is 90 deg.

A somewhat different condition would be approached at light load when the d-c circuit is noninductive. For large values of $\alpha$ the voltage of phase $a$ would be cut off at the zero point because the current would be cut off at that point. The voltage would remain zero until the grid control permits the next phase to fire. Thus in the 6-phase rectifier when the angle of retard is more than 60 deg, the voltage curve would have positive loops with dead spots between them, and an angle of retard of 120 deg would be necessary to reduce the output voltage to zero, as shown in the section entitled "Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

These considerations show that for a narrow range of voltage control, when the output voltage curve does not reach the zero line, the theoretical no-load voltage is independent of the characteristics of the output circuit. For a wide range of voltage control, when the curve reaches or crosses the zero line the no-load voltage curve which would be approached depends upon the characteristics of the output circuit.

The values of the harmonics in the no-load voltage wave with negative loops are obtained by substituting $u = 0$ in eqs 1 and 2. When the negative loops are cut off a separate analysis is required and eqs 14 and 15 for the harmonics are given later in the section entitled "Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

## Theoretical Wave Shape With a Noninductive Load

If the load on a rectifier is equivalent to a resistance, the current in the d-c side is pulsating. The voltage wave shape at a given load and output voltage is not the same as it would be with inductance in the d-c circuit if other conditions remain unchanged, because the angle of overlap $u$ and angle of retard $\alpha$ are different. For a given pair of values of $u$ and $\alpha$ the voltage wave shape is the same as in Fig. 2, if the effect of the pulsating current upon the inductance of the transformer and supply circuit is neglected, and if the curve does not cross the zero line. When the values of $u$ and $\alpha$ are known the values of the harmonic can be obtained by eqs 1 and 2.

Formulas for the angle of overlap and the output voltage $E_d$ for a given angle of retard $\alpha$ have been obtained by some authors,[6] but they are quite complicated. Formulas and curves obtained by a simplified analysis are given here. Results obtained

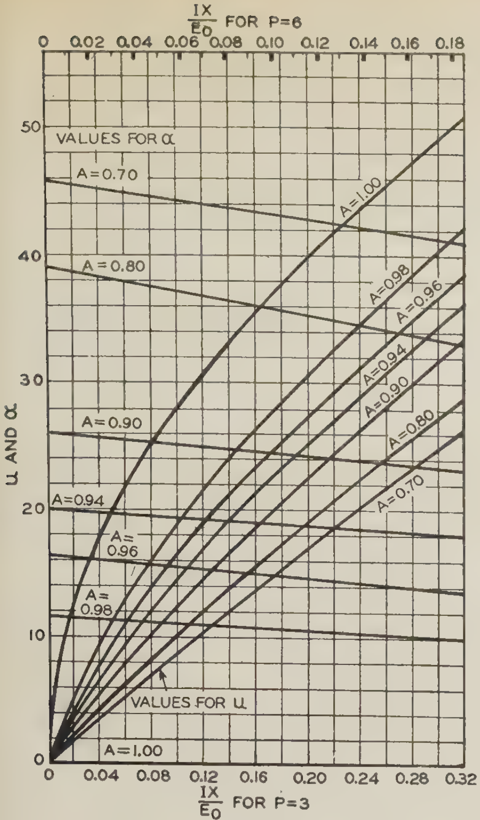



**Fig. 8. Angle of overlap, u, and angle of retard, $\alpha$, as functions of $IX/E_0$, for different values of voltage control ratio A**

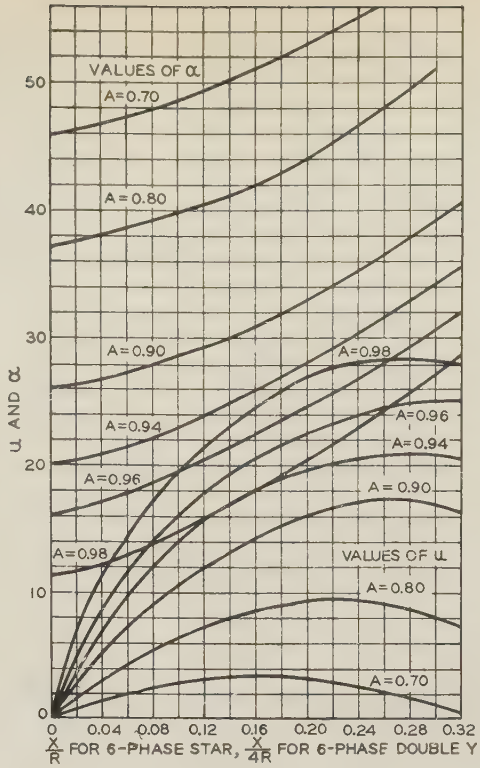



**Fig. 9. Angle of overlap, u, and angle of retard, $\alpha$, as functions of X/R for 6-phase rectifiers, for different values of voltage control ratio A and noninductive load**

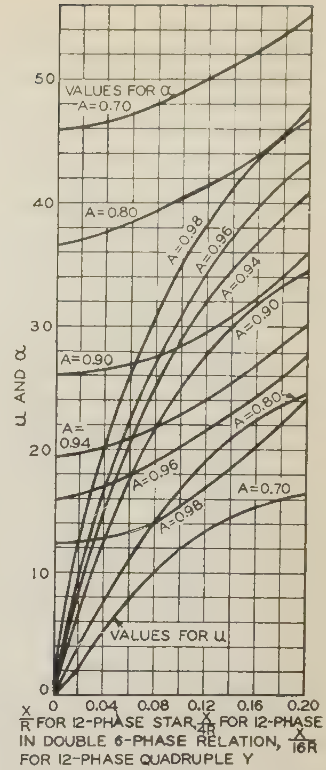



**Fig. 10. Angle of overlap, u, and angle of retard, $\alpha$, as functions of X/R for 12-phase rectifiers, for different values of voltage control ratio A and noninductive load**

for the 6-phase star-connected rectifier with the approximate formulas have been compared with results by the more elaborate formulas and have been found to be satisfactory for practical purposes when the commutating reactance is less than $^1/_4$ of the load resistance and the voltage reduction obtained with grid control is not more than 50 per cent. When interphase transformers are used the formulas must be modified and separate sections of this paper are given for rectifiers with 1, 2, and 4 groups of secondary phases.

*Rectifier With One Group of Secondary Phases.* It is assumed that when there is no overlapping between the currents in adjacent anodes, the current on the d-c side has the same shape as the voltage and is given by the formula

$$i = \frac{E_0}{R} \cos \theta$$

where

$E_0$ = peak value of voltage to neutral on the secondary side of the transformer
$R$ = load resistance (output voltage divided by load current)
$\theta$ = angular distance measured from point of maximum voltage

At the time when commutation begins the current is

$$I_1 = \frac{E_0}{R} \cos\left(\frac{\pi}{p} + \alpha\right) \tag{8}$$

where

$I_1$ = current on d-c side at beginning of commutating period
$\alpha$ = angle of retard of the anode firing period

If it be assumed that the current does not change during the commutating period, $I_1$ may be substituted for $I$ in eq 4 which gives the following relation

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{X}{R}\,\frac{\cos\left(\frac{\pi}{p}+\alpha\right)}{\sin\frac{\pi}{p}}\right)\right] - \alpha \tag{9}$$

where

$u$ = angle of overlap
$X$ = reactance of the circuit in which commutation takes place

The voltage under load is obtained by substituting eq 9 in eq 5. This gives the formula

$$E_d = \frac{E_{do}}{2}\left(2\cos\alpha - \frac{X}{R}\,\frac{\cos\left(\frac{\pi}{p}+\alpha\right)}{\sin\frac{\pi}{p}}\right) \tag{10}$$

The curves in Figs. 9 and 10 show values of $u$ and $\alpha$ plotted against $X/R$ for different values of voltage control ratio defined in the section entitled "Theoretical Wave Shape of a Rectifier Supplying a Highly Inductive Load." Figure 9 applies to the 6-phase rectifier and the curves were obtained by substituting $p = 6$ in eq 10. Figure 10 applies to the 12-phase rectifier and the curves were obtained by substituting $p = 12$.

Referring to eq 8 it may be noted that $I_1$ is zero when $\alpha = \pi/2 - \pi/p$. For larger values of $\alpha$ there cannot be overlapping and eqs 9 and 10 do not apply. This case will be discussed in the section entitled,

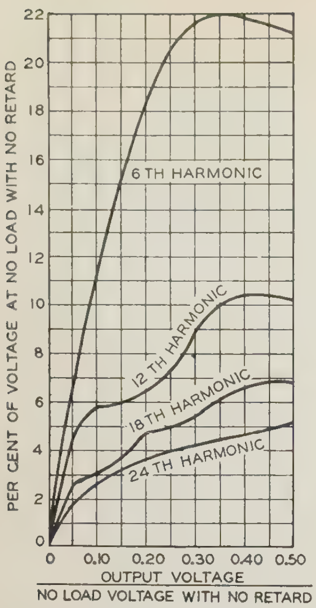



**Fig. 11. Percentage values of the 6th, 12th, 18th, and 24th harmonics in a 6-phase rectifier, plotted against the ratio of output voltage to no-load voltage with no retard and with noninductive load**

"Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

*Rectifier With 2 Groups of Secondary Phases.* The interphase transformer divides the load current equally between the 2 groups so that either group carries a current that at any instant is the average of the currents for the 2 groups when each carries a separate load of half the total load. In the following discussion $p$ represents the number of phases in each group and the angular displacement between the 2 groups is $\pi/p$. If the 2 groups are operated as separate rectifier units and the load in each is equivalent to a resistance $2R$, the current in group 1 at the beginning of commutation is

$$I_1' = \frac{E_0}{2R}\cos\left(\frac{\pi}{p} + \alpha\right)$$

At the same time the current in group 2 is

$$I_2' = \frac{E_0}{2R}\cos\alpha$$

When the 2 groups are connected through an interphase transformer and carry a load equivalent to $R$, the current in either group at the beginning of commutation is

$$I_1 = \frac{1}{2}(I_1' + I_2') = \frac{E_0}{2R}\cos\frac{\pi}{2p}\cos\left(\frac{\pi}{2p} + \alpha\right) \tag{11}$$

Substituting $I_1$ for $I$ in eq 4 the following formula for the angle of overlap $u$ is obtained:

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{X}{4R}\,\frac{\cos\left(\frac{\pi}{2p} + \alpha\right)}{\sin\frac{\pi}{2p}}\right)\right] - \alpha \tag{12}$$

For the 6-phase double-Y rectifier $p = 3$ and the curves on Fig. 9 may be used if $X/4R$ is substituted for $X/R$. Similarly the curves on Fig. 10 may be used for the 12-phase rectifier in double 6-phase relation by making the same substitution.

*Rectifier With 4 Groups of Secondary Phases.* In this case the groups of $p$ phases each are displaced by an angular distance of $\pi/2P$. If the groups are operated on separate rectifiers and the load on each group is equivalent to $4R$, the current in group 1 at the beginning of commutation is

$$I_1' = \frac{E_0}{4R}\cos\left(\frac{\pi}{p} + \alpha\right)$$

At the same time the currents in the other groups are

$$I_2' = \frac{E_0}{4R}\cos\left(\frac{\pi}{2p} + \alpha\right)$$

$$I_3' = \frac{E_0}{4R}\cos\alpha$$

$$I_4' = \frac{E_0}{4R}\cos\left(\alpha - \frac{\pi}{2p}\right)$$

When the 4 groups are connected by interphase transformers and carry a load equivalent to $R$, the current in each group at the beginning of commutation is

$$I_1 = \frac{1}{4}(I_1 + I_2 + I_3 + I_4)$$
$$= \frac{E_0}{4R}\cos\frac{\pi}{2p}\cos\frac{\pi}{4p}\cos\left(\frac{\pi}{4p} + \alpha\right) \tag{13}$$

The formula for $u$ obtained by substituting eq 13 in eq 4 is

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{X}{16R}\,\frac{\cos\left(\frac{\pi}{4p} + \alpha\right)}{\sin\frac{\pi}{4p}}\right)\right] - \alpha \tag{14}$$

For the 12-phase quadruple-Y connection, $p = 3$ and the curves on Fig. 10 may be used by substituting $X/16R$ for $X/R$.

### Method of Estimating Harmonic Voltages With Noninductive Load

In order to estimate the harmonic voltages with noninductive load the values of angle of overlap $u$ and angle of retard $\alpha$ may be obtained from the equations or the curves and substituted in eqs 1 and 2. Sets of curves similar to Figs. 3 to 6 might be plotted from which the percentage values of the harmonic could be obtained directly from the values of $X/R$ and the voltage control ratio, but the formulas in the preceding section show that separate sets of curves would be required for 6-phase rectifiers and 12-phase rectifiers.

However, the curves on Figs. 3 to 6 may be used for the case of noninductive load in the following manner: Find the values of $u$ and $\alpha$ from Fig. 9 or 10, or by the formulas. Then refer to Fig. 8 and find by trial the pair of values of $IX/E_0$ and voltage control ratio that give the same values of $u$ and $\alpha$. Then read the percentage values of the harmonics from Figs. 3 to 6 corresponding to these values of $IX/E_0$ and voltage control ratio. This will be understood better by considering a numerical example. A rectifier connected double-Y 6-phase is loaded on a noninductive resistance of 0.6 ohm. The commutating reactance is 0.17 ohm. The voltage is reduced 10 per cent by grid control. It is desired to estimate the harmonic voltage on the load side for this condition. Since there are 2 groups of secondary phases the ratio $X/4R$ is calculated and found to be

0.071. Then from the curves for $A = 0.90$ on Fig. 9 the values $\alpha = 28$ deg and $u = 8.5$ deg are obtained. Referring next to Fig. 8, it may be noted that $A$ is approximately 0.89 for $\alpha = 28$ deg. Using this as a first approximation it is found that $IX/E_0$ on the lower scale is 0.065 for $u = 8.5$ deg. Checking again, it may be seen that $\alpha = 28$ deg corresponds to $A = 0.89$ at $IX/E_0 = 0.065$. Referring to the curves on Figs. 3 to 6 and reading the harmonics for $A = 0.89$ and $IX/E_0 = 0.065$ on the lower scale, the percentage values are approximately as follows:

| | |
|---|---|
| 6th harmonic | 14 per cent |
| 12th harmonic | 5 per cent |
| 18th harmonic | 1.3 per cent |
| 24th harmonic | 1.4 per cent |

## Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control

It has been pointed out in the subsection entitled "Rectifier With One Group of Secondary Phases" that when the angle of retard is equal to $\pi/2 - \pi/p$, the load current is zero at the end of the conducting period for each phase and there cannot be overlapping. If $p$ is replaced by $p'$, which represents the total number of secondary phases, this relation holds for rectifiers either with or without interphase transformers. In a 6-phase rectifier the current is zero when the angle of retard is 60 deg, and in a 12-phase rectifier when the angle of retard is 75 deg.

When the angle of retard is greater than $\pi/2 - \pi/p'$ (greater than 60 deg for a 6-phase rectifier or 75 deg for a 12-phase rectifier) the voltage curve is cut off at the zero line and is similar to Fig. 12. The voltage curve for this condition has been analyzed to obtain a Fourier series and the coefficients of the $m$th sine and cosine terms are, respectively,

$$a_m = -\frac{E_{do}}{(m^2p'^2 - 1)\sin\frac{\pi}{p'}}\left[\sin\frac{mp'\pi}{2} - mp'\cos mp'\alpha\cos\left(\alpha - \frac{\pi}{p'}\right) + \sin mp'\alpha\sin\left(\alpha - \frac{\pi}{p'}\right)\cos m\pi\right] \quad (15)$$

$$b_m = -\frac{E_{do}}{(m^2p'^2 - 1)\sin\frac{\pi}{p'}}\left[\cos\frac{mp'\pi}{2} + mp'\sin mp'\alpha\cos\left(\alpha - \frac{\pi}{p'}\right) - \cos mp'\alpha\sin\left(\alpha - \frac{\pi}{p'}\right)\cos m\pi\right] \quad (16)$$

The rms values of the harmonics are obtained by substituting the values of $a_m$ and $b_m$ in the formula

$$h_m = \frac{1}{\sqrt{2}}\sqrt{a_m^2 + b_m^2}$$

The output voltage is given by the formula

$$E_d = \frac{E_{do}}{2\sin\frac{\pi}{p'}}\left[1 - \sin\left(\alpha - \frac{\pi}{p'}\right)\right] \quad (17)$$

where $p'$ is the number of secondary phases, and the other symbols are as defined under eqs 1, 2, and 5. The phases of the harmonic voltages referred to the maximum point of the applied voltage can be obtained from eqs 15 and 16. It may be noted that when $\alpha = \pi/2 + \pi/p'$ (120 deg for a 6-phase rectifier and 105 deg for a 12-phase rectifier) the output voltage is zero.

**Fig. 12. Output voltage wave shape of controlled voltage rectifier with angle of retard greater than $\pi/2 - \pi/p$**

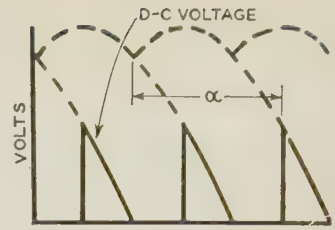



Figure 11 shows the percentage values of the 6th, 12th, 18th, and 24th harmonics in the 6-phase rectifier with noninductive load plotted against ratio of output voltage to theoretical no-load voltage with no retard.

The equations and curves given here apply to rectifiers with 1 group of secondary phases and also to the theoretical case of 2 or more groups of secondary phases with the load current equally divided between the groups at all times. This ideal condition cannot be realized with actual interphase transformers when the load current is less than their magnetizing current. Since the load current is zero at the end of the conducting period when the angle of retard exceeds $\pi/2 - \pi/p^1$, it appears that the curve of Fig. 12 may have to be modified when interphase transformers are used. The output voltage of a 6-phase rectifier with an interphase transformer is discussed in a recent paper[7] and curves are constructed on the basis of certain assumptions. One curve is obtained for values of angle of retard between 60 and 90 deg and another for values of angle of retard greater than 90 deg. The latter curve is similar to that of Fig. 12 and the former could be analyzed into component curves, each of which would be similar to that of Fig. 12. In either case the magnitudes of the harmonics could be obtained with the aid of eqs 15 and 16 by finding appropriate values of $\alpha$. In the case mentioned last it would be necessary to calculate the phases of the harmonics in the component curves in order to obtain the resultant harmonics.

It may be assumed as a first approximation that eqs 15, 16, and 17 apply to all loads. This neglects the interval of time required for building up the current from zero to the maximum value when each phase begins to carry current. However, the values of the harmonics obtained by neglecting this time interval are greater than those actually in existence because this time interval is produced by the smoothing effect of transformer inductance upon the load current and voltage.

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# A 100-Kw Vacuum Tube

**The construction of a new vacuum tube having a rating of 100 kw is described herewith.* This tube has been made possible by the development of water cooling and a satisfactory copper-glass seal.**

OVER 500 vacuum tubes in parallel were used for the first transatlantic radio telephone conversation in 1915. Since then vacuum tubes have undergone almost continuous development. The application of water cooling has permitted much larger capacities, and the present long wave transatlantic channel employs but 30 tubes, each of 15-kw rating. Further improvements in design and manufacturing technique have made possible still higher ratings. A tube is now available—the 265*A*—which has an anode dissipation of 100 kw. Six of such tubes will provide a greater output than the 30 employed for the present transatlantic service.

This radical increase in capacity, which has made it possible to obtain outputs of as many kilowatts as have formerly been obtained in watts, has been made possible by 2 developments. The limitation to capacity is largely a matter of dissipating the heat generated in the tube. By employing water for cooling the anode surfaces, however, the amount of heat that can be carried away has been greatly increased. This method of cooling has in turn been made possible to a large extent by the development of a satisfactory copper-glass seal. Neither water cooling nor the copper-glass seal were used for the first time with the new tube, but the technique of employing both of them has been recently improved.

## Copper-Glass Seal

A simplified cross section of the new tube, Fig. 1, shows the construction. The copper tube forming the anode is slightly flared at each end, and then these flared ends are carefully machined to a thin knife edge. Next, the anode is supported on an expanding mandrel of a lathe-like machine whose end chucks rotate coaxially and in synchronism. An open ended glass bulb is then mounted in one of the end chucks, and flames for heating the entire mass, and other flames to provide a high concentration of heat, are lighted and the machine is started.

The clean copper surface adjacent to the glass is first allowed to oxidize until the correct surface condition is obtained. This oxide layer must have sufficient elasticity to take up the strains caused by slight differences in the coefficients of expansion of copper and glass. Next, the glass is softened and spread over the copper surface by an ingenious roller tool supported on the center axis of the machine. This same tool also carries a nozzle through which is forced a stream of nitrogen to blow the glass bulb into the final shape desired. Following this, the process is repeated for the bulb at the other end of the anode. After the seals have been made, the ends of the bulbs are temporarily closed with an ionization manometer sealed to one of the bulbs, and the completed anode assembly is evacuated and baked. Manometer readings are then taken periodically over an extended interval to make sure there are no small leaks in the copper or the seal before the filament and grid structures are sealed in.

## Water Cooling

The cooling water passes at high velocity in the narrow space between the copper anode and an outer copper sleeve which is brazed to it before the copper-glass seal is made. Two water ports at each end of the outer sleeve give entrance and exit to the water, and also serve as points of support for the tube. This outer sleeve when brazed to the anode is in 2 parts. These 2 parts slightly overlap near the middle and are left open until the final degassing of the finished tube has been completed. Were it not for this provision, the high temperatures attained by the tube during the degassing process would cause a differential expansion of the copper anode and the outer copper sleeve, which being in direct contact with the air is much cooler, and would cause harmful strains in the copper structure.

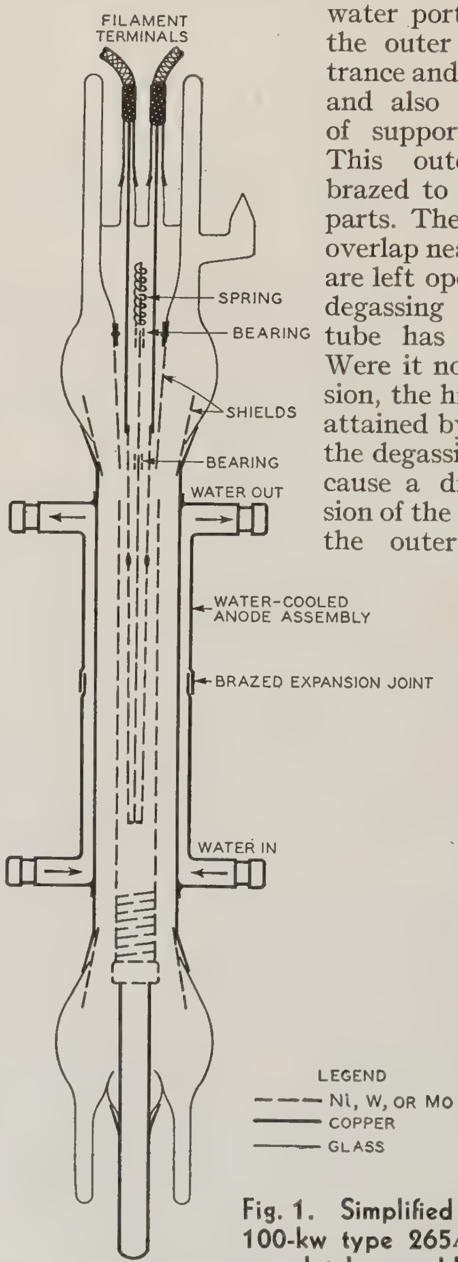


**Fig. 1. Simplified cross section of the 100-kw type 265*A* tube. The tube, completely assembled, is over 4 ft long**

## Filament and Grid Structures

The design of the filament structure is unique in employing no insulating supports at the ends of the V's, and in a very

* Essentially full text of an article "A New 100-kw Vacuum Tube," by H. E. Mendenhall (A'26), Bell Telephone Laboratories, Inc., New York, N. Y., and published in *Bell Laboratories Record*, v. 12, Dec. 1933, p. 98–102. *Not published in pamphlet form.*

simple arrangement for maintaining the filaments under tension. The apexes of the 3 filament V's hang downward and are passed over tungsten hooks within a molybdenum cap which fits loosely over a shoulder on a heavy central support rod. This rod passes through 2 bearings—7 in. apart—at its upper end, and is free to slide in them so that its weight maintains a tension on the filaments. Additional tension is obtained by a large coiled tungsten spring at the upper end which, fastened to the frame, exerts a downward pressure on the rod. The molybdenum supports of the upper ends of the filament V's are cross-connected and welded to the 2 copper leads which in turn are silver soldered into copper rods hollowed out to thin-walled tubing extending to the glass seal. This construction allows a further drop in temperature of the materials between the filaments and the copper-to-glass seals. The main support of the filament structure is obtained from a large copper-to-glass seal enclosing the upper filament rod bearing. This end of the filament assembly is enclosed with nickel sheet to provide a protective electrostatic shield to prevent destructive discharges at the high operating anode potential of 18,000 volts. Other vital points such as the anode seals are also protected by electrostatic shields.

metal parts are heated by external torching, filament glowing, and grid bombardment. During the pumping process the entire structure is maintained at very high temperatures, much higher than exist during ordinary operation, so as to free the high-melting-point metals from occluded gases. The temperature of the anode becomes so great that high velocity air streams for cooling are required to keep it from collapsing. The nickel shields within the tube are degassed by induction heating. It is these high temperatures that necessitate a break in the outer copper sheath to prevent large differential expansion. At the end of the degassing processes the 2 parts of this outer sleeve are brazed together since it and the anode will hereafter be at approximately the same temperature due to the cooling water.

In Fig. 3 is shown a group of completed tubes installed in an experimental transmitter at the Whippany laboratory which has been the proving ground for these tubes. For shipment, the tubes are packed in sturdy crates with spring suspensions so that the tube practically floats in the compartment. The flexible copper braids for the filament leads, which carry approximately 200 amp when the filaments are lighted, are anchored back to a band support collar when not in use.

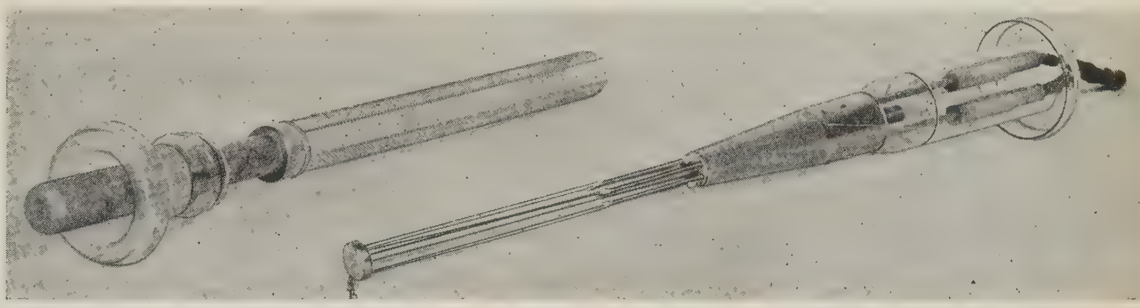

**Fig. 2. Grid structure (left) and filament structure (right) of the 265A tube**

The 3 filament V's are connected in parallel and have an active length of more than 4 ft. About 4,000 watts are required for heating, which maintain the filaments at a temperature above 2,500 deg K and give an electron emission of over 30 amp.

The grid structure, which is supported from the opposite end of the tube, is shown with the filament structure in Fig. 2. The grid must be kept below a temperature of 1,100 deg K to prevent the emission of primary electrons when it is negative with respect to the other electrodes. This is accomplished by using relatively more and larger grid verticals and fewer laterals than are normally used, and in employing a large copper support structure which is cooled by the natural upward draft around the tube. Heat readily flows down the large cross section of the grid verticals to the copper support, which has a bright heat shield to reflect from it the heat from the filament that would otherwise be absorbed.

### Removal of Gases

The completely assembled tube, which is over 4 ft long, requires a long exhaust process, involving constant attendance for about 24 hr. Special split ovens are placed around the glass parts of the tube, and the

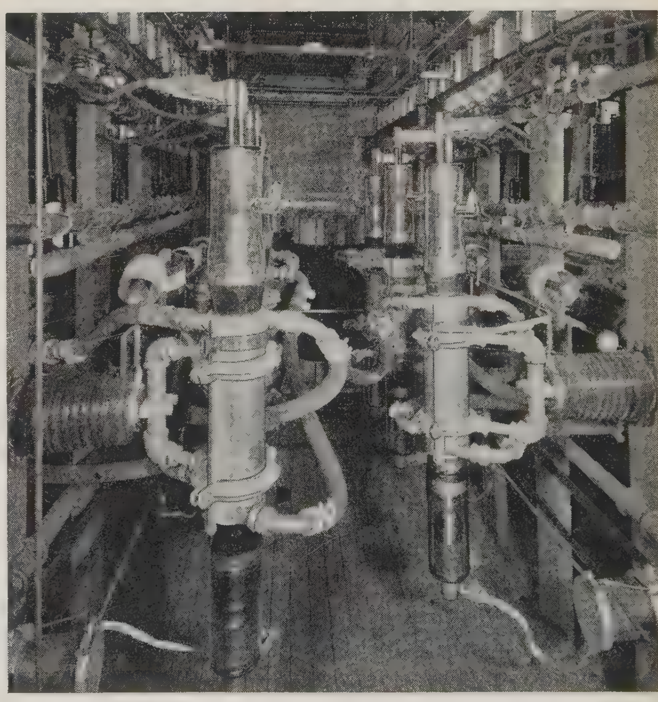

**Fig. 3. A group of 265A tubes installed in an experimental transmitter at Whippany**

# Machine Characteristics for Steady Welding

**The machine characteristics needed for steady welding have been analyzed with the aid of a series of tests of the welding process. In addition to describing the method of test, oscillograms and photographs of specially secured metal test strips are presented, and a discussion of the possible theory to explain the results is given in this paper.**

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AN ATTEMPT to ascertain by a direct study of practical welding operations what the characteristics of a generator really ought to be in order to give the steadiest welding is presented in this paper. It is the consensus of opinion of operators that modern welding generators with controlled transients operate more steadily than the older type. While many suggestions have been made as to why this should be, none of these has been pushed to the point of demonstration.

## Method of Tests

The method adopted in the following tests (used previously by Prof. G. E. Doan) has been to lay a bead of metal from a fixed electrode on to a moving strip, the motion of this strip being synchronized with an oscillograph so that the relation between metal deposited, current and volts is made apparent. In order to do this (see Fig. 1) a rest is provided opposite a revolving drum $A$. This rest, which is of insulating material, is for the welding electrode. The electrode is held in the rest by a skilled welding operator who advances or retires it from the work by hand so as to obtain the best possible arc. It was found that more sensitive regulation of the arc could be obtained from a hand operator than from any automatic device available to us. To the drum is attached a strip of metal screwed to its circumference, which can be replaced as often as necessary. The drum is driven by a small motor through slow motion gear consisting of belts and pulleys $E$ and on the same shaft is a spur wheel $B$ having 120 teeth. A small finger $D$ makes contact with these teeth as the wheel turns, thus completing a circuit and giving a make and break arrangement. In addition a slip ring $C$ serves to carry the current to the work, which revolves with the drum.

At one point the space between 2 teeth is filled in with solder so that at this point contact lasts 3 times as long as elsewhere. If the record corresponding to this point, called the initial point, is included in an oscillogram and we count the number of makes and breaks on it from the initial point to the point we desire to study, which is of course equal to the number of teeth starting from the initial point, we can locate the exact point on the strip which corresponds to any given point on the oscillogram. This is the way in which the synchronization is effected. The circuit through the spur wheel is excited with alternating rather than direct current so that the same oscillograph vibrator may serve at once to give the make and break and a timing wave. The effect of this is shown in most of the oscillograms of this paper, where we see at one point a series of alternations much wider than at others. This is the initial point, of course, and it is followed by a break and this by other series of alternations which correspond to other teeth. The whole apparatus is very simple, and easily arranged and mounted for either direct or overhead welding, and enables us to reach a number of interesting conclusions.

## Procedure of Testing

The procedure in making a test is as follows: After all the apparatus has been adjusted, put the drum into starting position, that is with the bead starting at the top of the test strip. The operator then strikes his arc and gets it into a steady condition with the drum stationary. He then sets the drum in motion by pressing a foot switch at the same time

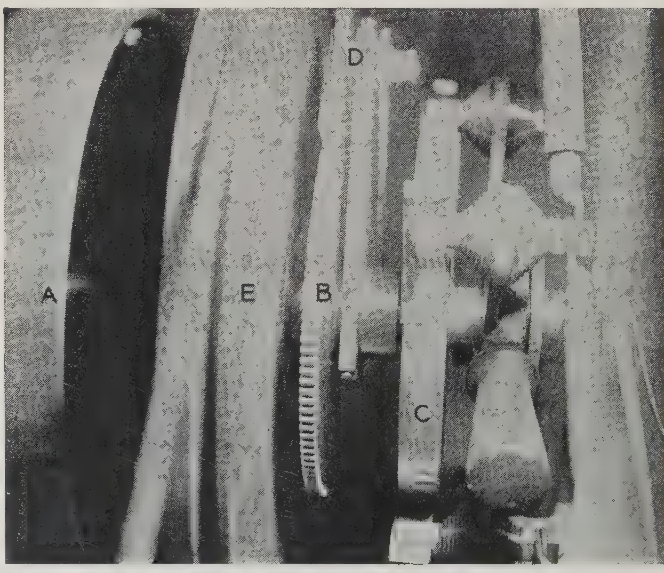



Fig. 1. Device used in tests

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding. Manuscript submitted Nov. 16, 1933; released for publication Feb. 28, 1934. *Not published in pamphlet form.*

giving a signal to the oscillograph operator who records the film as the bead is laid along the test strip. At the end of the run the operator states his opinion of the type of welding, that is "steady," "unsteady," etc.

When the experiment has been completed, the test strip has to be photographed and enlarged to such a size that the distance between the ends of the parts to be studied is equal to the length of the film. Finally the film and the photograph of the strip must be printed side by side as shown in the figures. A large number of records were made in this manner, some of which show extremely interesting results.

Records which were reported as corresponding to steady welding are shown in Figs. 2 to 7. These records were taken with a number of different types of coated wire. These were merely the kinds that happened to be at hand and no inference must be made from these records as to the relative advantages of these types of coating.

### The Long Arc

Of these records possibly No. 3 is the most striking. Notwithstanding the deposition of a fairly heavy bead there was no short circuit of the arc opposite the greater part of the bead; in fact only 3 points of momentary short circuit can be seen in the film each of which seems to correspond to a rather larger drop than elsewhere. This seems to show conclusively that metal can be deposited in considerable quantities without short-circuiting the arc and therefore proves that every drop which passes does not necessarily short-circuit it. This is the type of operation which is found when a rather long arc is used.

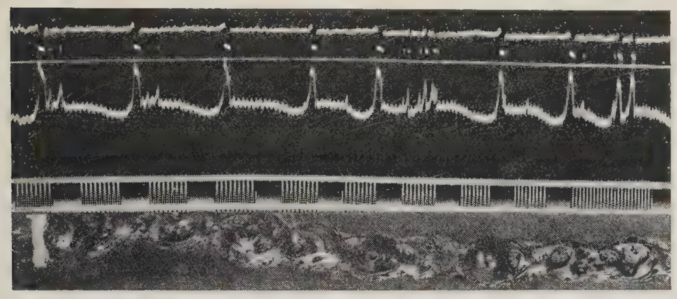


**Fig. 2. Steady welding. 135 amp. 32 volts. Electrode positive. Fleetweld electrode**

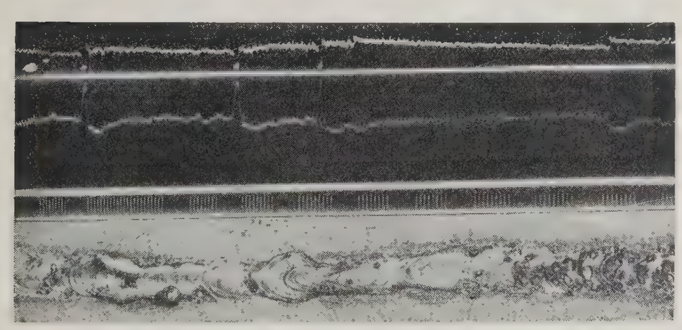


**Fig. 3. Steady welding. 140 amp. 29 volts. Electrode positive. A.W.P. electrode**

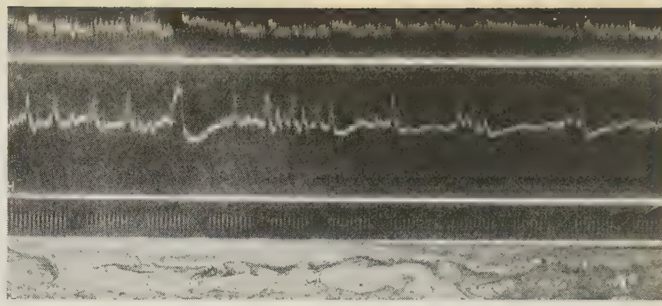


**Fig. 4. Steady welding. 150 amp. 20 volts. Electrode negative. Murex electrode. Series connection coils. Short arc**

This confirms the result reported by E. C. Easton and F. B. Lucas in the discussion (see Trans. A.I.E.E., v. 51, 1932, p. 564) of "Forces of Electric Origin in the Iron Arc," of which one of the present authors was a co-author. It was there shown by synchronizing the oscillograph with a movie camera that no disturbance whatever could be noticed in the current and voltage recorded on the oscillogram when a drop was observed to pass across the arc as photographed by the movie camera. The writers still adhere to the explanation given in that paper of the passage of the drop, namely, that as stated in the reply to the discussion: "According to our view the function of the pinch effect is solely to separate the globule from the electrode and if there were no other forces in existence when the globule had been so separated it would fall to the ground under the action of gravitation. Our view is that the pinch effect separates the globule which is then taken across by the forces measured in the first part of the paper, and these forces, which have nothing whatever to do with the pinch effect and which are measured but not explained in the paper, are those which are responsible for carrying the globule over." [Authors' Note: Since this was written these forces have been tentatively explained as due to a fine spray of particles projected by each electrode.]

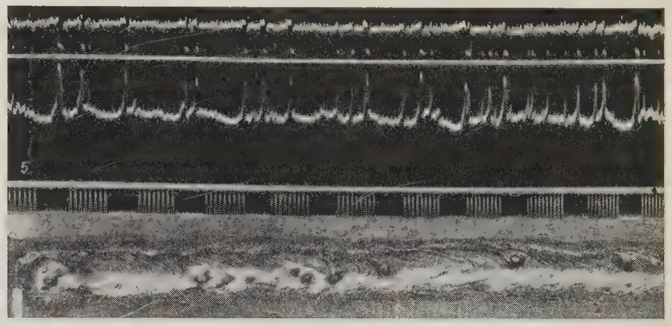


**Fig. 5. Steady welding. 135 amp. 32 volts. Short arc. Electrode negative. Fleetweld electrode**

### Unsteady Welding

The oscillogram reproduced in Fig. 9 is reported as corresponding to unsteady welding. It will be seen that in this case the short circuits are far from being regularly periodic and the mean current also is not constant. This record shows in addition that every drop did not short-circuit the arc while notwithstanding this the deposit consists of a regular series of drops.

### Overhead Welding

The oscillograms reproduced in Figs. 9 and 10 show overhead welding. Although there is a deposit which is slighter than with welding in the normal position, there are nevertheless no short circuits shown in Fig. 9 and only a few in Fig. 10,

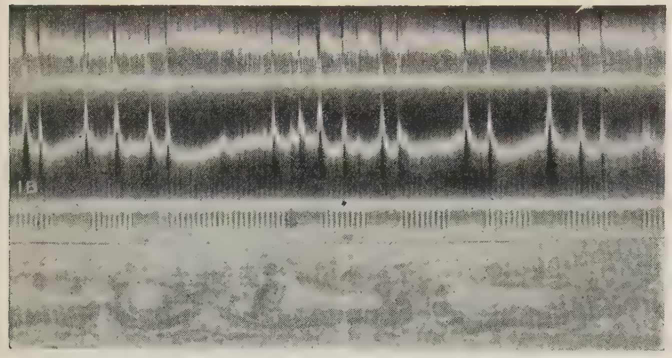


Fig. 6. Steady welding. 125 amp. 32 volts. Electrode negative. G. E. electrode

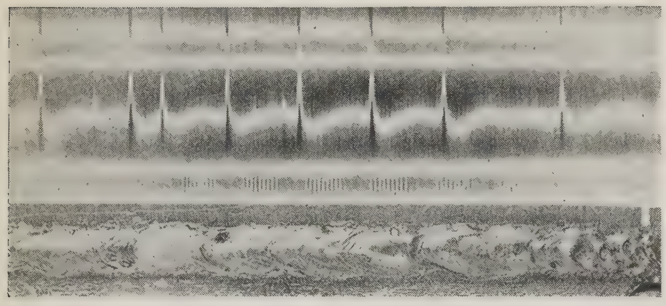


Fig. 7. Steady welding. 140 amp. 28 volts. Electrode positive. G. E. rod

which show again that some other mechanism than short-circuiting the arc serves to transfer the metal. These 3 oscillograms show another striking phenomenon to which we shall return later.

### The Short Arc

The oscillograms reproduced in Figs. 2, 4, 5, 6, and 7 are also reported as corresponding to steady welding. These show the conditions corresponding to a short arc. Although there are a large number of short circuits, these are regularly periodic or tend to be so. It should be noted that the generator which was used in these tests was of a modern type with controlled transients and was capable of holding the average current between short circuits nearly constant, notwithstanding variations of arc conditions.

### Conclusions From the First Series of Tests

Thus the conclusions we obtain from the examination of these oscillograms are that steady welding may take place either with no short circuits in case of a long arc or with regularly periodic short circuits in the case of a short arc. If the short

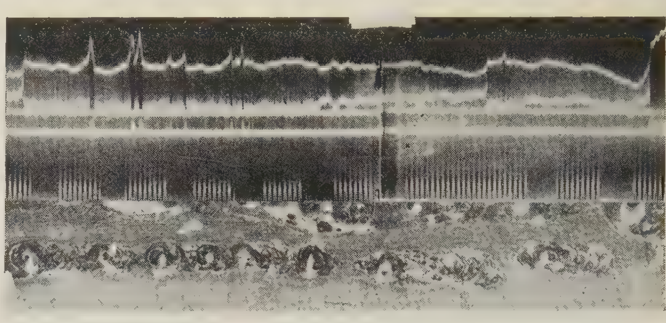


Fig. 8. Unsteady welding. 160 amp. 32 volts. Electrode negative. Fleetweld electrode

circuits are to be regularly periodic, this means that the rate of evolution of heat must be steady so that the tip of the rod is heated to melting point and passes across in the form of a drop at regular intervals. It has been shown that within the welding range (see "Performace and Design of Electric Welders with Controlled Transients," by F. Creedy, Trans. A.I.E.E., v. 52, 1933, p. 268–78) the voltage across the arc is entirely independent of the current and only increases slightly with increase in arc length. Hence for a given arc length the rate of evolution of heat is directly proportional to the current. Thus a steady rate of evolution of heat means a steady mean current. The old argument between "constant watts" and "constant current" is seen to be meaningless since on account of the constancy of the arc voltage constant current results in constant watts.

As a result of the above observations we are now able to state why the modern machine with controlled transients is superior to the older type. It is well known that the best welding is done with a short arc which keeps the mass of metal hot and does not fly around in a way the long arc sometimes does. It is also agreed by operators that with the controlled transient machine it is possible to hold a shorter arc than with the old type.

According to the view here put forward, the shorter limit for arc length is reached when the arc short-circuits so frequently that it is unable to maintain its temperature and so sticks. Of course during the short circuit there is no arc and therefore the amount of heat being evolved is much reduced. As the short circuits become fewer the arc is in existence for a longer period of time and therefore more heat

is evolved. There must therefore be some arc length for which the number of short circuits per second is sufficient to transfer an ample amount of metal and yet few enough to maintain a high temperature. This is the minimum useful arc length. Beyond this limit the amount of metal transferred is reduced with probably very little further increase in temperature and in fact as the electrode is removed from the proximity of the work it may actually cool. When holding a short arc therefore it will be clear how important a machine with rapid "pick-up" is. If it takes a considerable time for the arc to recover after every short circuit it is clear that if the short circuits per second are numerous the arc will cool and the electrode stick. Hence a machine with slow pick-up compels us to hold rather a long arc with comparatively few short circuits per second.

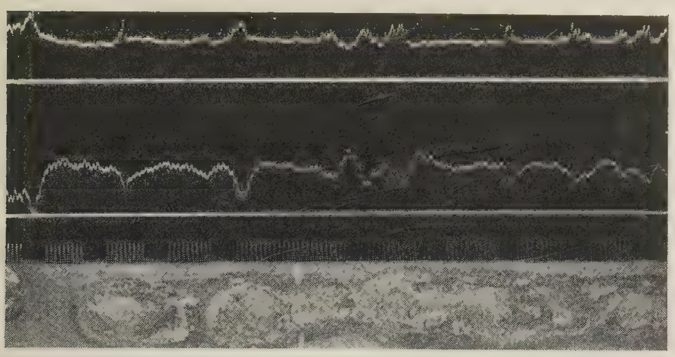


Fig. 9. Steady overhead welding. 140 amp. 35 volts. Electrode negative. Cresta murex electrode

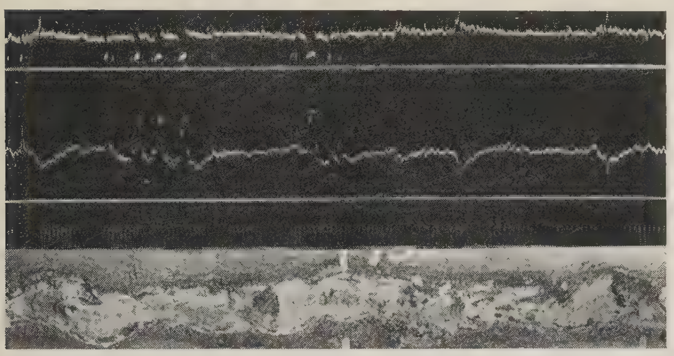


Fig. 10. Steady overhead welding. 150 amp. 32 volts. Electrode negative. Cresta murex electrode

If, on the contrary, recovery is nearly instantaneous as in the machine used (which was the neutralized welder described in a previous paper) a much greater frequency of short circuit can be permitted before the heat evolved is reduced too much. It is perhaps as well to state emphatically here our belief that the metal is transferred in the form of a rapid succession of drops of about the same diameter as the electrode.

It was seen above that uniform evolution of heat was necessary to steady welding and this depends upon the mean current remaining constant. The older type of machine having large slow-period transients could not maintain a steady mean current but the modern type is far more capable of doing so. If we contrast, for instance, such an oscillogram as that reproduced from an old machine in the lower part of Fig. 7, p. 660 of the A.I.E.E. TRANSACTIONS for June 1931 ("An Improved Arc Welding Generator," by J. H. Blankenbuehler) with those taken by modern machines (for instance, the oscillogram immediately above that just referred to) it can easily be seen that the older type of machine showed marked variations in mean current as well as irregularities in the number of short circuits per second.

The main object of the present paper is to form a rational theory such as that outlined in the paragraphs above of why the modern machines with controlled transients are superior to the older type.

To summarize, in our opinion the improvement is due:

1. To reduced (though not eliminated) current kicks during short circuit.

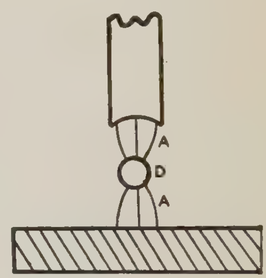
2. To rapid "pick-up" after short circuit thus maintaining the heat of the arc.

3. To constant mean current due to the absence of slow period current transients.

A number of further conclusions of interest arise from the same study. Although as shown in a paper by one of the writers "Performance and Design of Electric Welders With Controlled Transients" (previously referred to) the machine used gave a rise

Fig. 11. Diagram for possible explanation of current dips

A. Arc. D. Drop



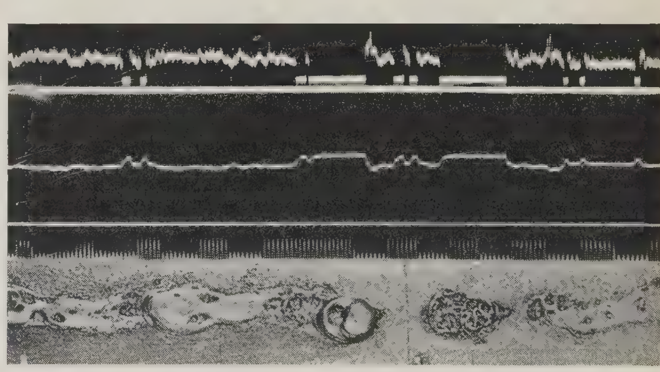



Fig. 12. Welding with ballast resistance. 140 amp. 22 volts. Bare wire negative. Good in places

of current of only about 30 per cent during momentary short circuit, nevertheless, in actual welding the percentage rise of current seems in some cases to be higher than this. This would seem to indicate that there was still something about the welding circuit not fully explained, probably connected with the actual characteristics of the arc. The rise of current during short circuit is, however, much less than in older types of machine.

### Greater Copiousness of Deposit With Coated Rods

Another interesting point brought out by the experiments is the much greater copiousness of the deposit with coated rods. Several explanations may be suggested for this:

1. The reduction of surface tension in the molten drop permits it to separate more easily. This is a true fluxing action.

2. Akin to this explanation is the following: the reduction of the oxide layer on the surface of the molten drop has the same effect of enabling it to separate more easily. This is, therefore, a kind of fluxing also.

3. The mere fact that the coating of the rod is of a material which is a poor conductor of heat serves to blanket it and prevent the escape of heat, thereby leading to more rapid melting.

### Current Dip During Overhead Welding

Returning to Figs. 9 and 10 relating to overhead welding, it will be noted that these show a phenomenon just opposite to that of short-circuiting which involves a rise of current accompanied by a drop of voltage. In these figures we see sharp dips in the current accompanied by a corresponding rise in voltage. In Fig. 9 there are no short circuits while in Fig. 10 there are both short circuits and dips as well. The likeliest explanation for these dips is the following. When a drop is detached from the electrode it ordinarily ceases to carry current unless it short-circuits the arc. If it does not short-circuit the arc then the arc continues to carry the current while the drop passes over without doing so. But in certain cases the arc may pass from the electrode to the drop and from the drop to the work in a manner shown in Fig. 11. In this case since there are 2 arcs there will be 2 cathode and 2 anode drops of potential and hence the voltage across the arc will be approximately doubled. If we suppose that this is what happens when a dip of current occurs this will suffice to explain it but of course a more direct proof that this explanation is correct would be desirable.

### Welding With Ballast Resistance

In Fig. 12 is reproduced an oscillogram taken when welding was carried out by using the 110-volt supply from a battery with a ballast resistance and self induction in series, instead of using the welding generator. This oscillogram is reproduced chiefly to show the much greater smoothness of the current wave. Nevertheless the high frequency oscillations in the voltage wave are not wiped out so that it would be interesting to know their origin.

# Equivalent Circuits in Stability Studies

**Representation of "receiving-end" systems by simplified equivalent circuits, for use in steady state stability studies of electric power transmission systems, is discussed in this paper. Various methods of approximate representation are analyzed, compared, and evaluated. Comparative analyses of a specific problem indicates that the simplified method that replaces the receiving-end system by an equivalent generator and an equivalent load is sufficiently accurate for engineering purposes.**

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TO FACILITATE stability studies and calculations, the complicated networks comprising electric power transmission systems may often be represented by simplified equivalent networks which may be used in place of the actual networks. In this paper the general problem of "receiving-end" system representation in stability calculations is discussed, and a limited number of comparative analyses based upon somewhat different premises are presented. The particular problem analyzed is that of a hydroelectric station connected by a long transmission line to an existing system (called the receiving-end system) consisting of generating stations, substations, and loads. This paper presents also a method of obtaining the receiving-end system characteristics by use of a network analyzer, which may be of value for the solution of some types of practical problems.

In order to determine the validity and accuracy of approximate methods of receiving-end representation, 2 sets of stability analyses of a specific system were made; the first an exact representation, and the second an approximate representation by an equivalent generator and an equivalent load. As far as it is permissible to draw general conclusions from these analyses of a single although typical and fully representative power transmission system, it is evident that the method involving the equivalent generator and equivalent load representation of the receiving-end system gives results of engineering ac-

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curacy. Both the resultant power-voltage and reactive power-voltage characteristics are in good agreement with the correct ones when actual load characteristics are assigned to the equivalent load. The power limits obtained by the 2 methods also are in close agreement.

The assumption of constant-impedance loads does not affect the power characteristics materially, but does influence the reactive-power characteristics to an appreciable extent. In the exact method of analysis the use of constant-impedance loads gives rise to essentially the same power limit as when actual load characteristics are used. In the approximate method, however, the power limit obtained with constant-impedance equivalent load deviates to a somewhat larger extent from that based upon actual load characteristics. It is impossible to say, of course, whether the use of constant-impedance loads might not give rise in other systems to larger discrepancies than here indicated.

To sum up, it seems that the simplified method, which replaces the receiving-end system by an equivalent generator and an equivalent load directly at the receiving-end bus, is sufficiently accurate for engineering purposes. For maximum reliability of results it appears preferable to assign load characteristics to the equivalent load, in the manner discussed, rather than to represent it by a constant impedance.

## General Problem

In connection with long distance transmission of electric power the problem most frequently encountered is the following: A water power site usually is developed for the purpose of increasing the power available at some large load area. In general the locations of the available water power and the load area are far apart, and transmission over long lines therefore becomes necessary.

At the load area the transmission line ties in with an existing system. This, as a rule, will contain several generating stations, substations, and loads of various categories. In connection with the design of the transmission line it usually is sufficient to ascertain that the hydroelectric station will operate with stability with respect to the receiving-end system. The problem therefore narrows down to an examination of the stability of the line, or rather the transmission system, and is carried out without reference to the stability situation within the receiving-end system itself.

It may be appropriate, therefore, in a situation of this sort to treat the receiving-end system as a unit. This may be done by simulating its performance at the point at which the transmission line ties in (usually the low voltage side of the receiving-end substation) by a set of power-voltage and reactive power-voltage characteristics. These characteristics in general are based upon operation at constant field current of the various main synchronous machines within the receiving-end system and with connected loads of designated values.[1,2]

It is evident that these receiving-end system characteristics are motor characteristics in the sense that they indicate the input to the receiving-end system taken as a whole. In other words, this method of representation treats the receiving-end system as if it were an equivalent motor. In order to determine whether stability is present between the 2 systems, the equivalent motor characteristics may be superimposed on the receiving-end characteristics of the transmission system. The procedure involved (analytical or graphical, as the case may be) is exactly the same as that used in connection with the stability of simple systems with synchronous motor loads.[1,3] The fact that an equivalent motor is dealt with does not change the principles involved in the analysis.

Having carried out the superposition, a resultant power-voltage curve is obtained, as indicated in Fig. 17. In regard to the interpretation of this characteristic, caution must be exercised. It is safe to say that if the curve shows convexity (i. e., indicates that a power increment is associated with a drop in voltage) the transmission system will be stable with the connected loading assumed. While the maximum point on this curve definitely signifies the power limit when an actual synchronous motor constitutes the load, *it has no similar significance in the present case because the receiving-end system is in reality no motor*. This is an important point and should be borne definitely in mind.

It usually is required, however, to determine the power limit of the transmission system when operating at normal voltages. In order to obtain this limit recalculations are in general necessary. Assuming that the first power-voltage curve indicates stability, the loadings within the receiving-end system are increased and its junction point characteristics revamped to correspond to the new load conditions. (Looking at the receiving-end system as an equivalent motor, this procedure is evidently equivalent to changing its capacity.) The stability is checked again by superposition and inspection of the resultant power-voltage curve. Recalculations in this manner are made until the power limit can be ascertained.

It is obviously not necessary to hit at the *exact* load conditions that will correspond to the power limit. The actual value may be obtained by extrapolation when a sufficient number of power-voltage curves are available. The limit is obtained at the point of intersection between the normal voltage axis and a curve representing the locus of maxima (Fig. 17).

This method, involving the use of receiving-end system characteristics based on actual load conditions within the receiving-end system, is an effective and correct one for the particular purpose for which it is applied. It serves to indicate correctly whether or not synchronizing power between the 2 parts of the system, i. e., the transmission line and the receiving-end system, is present. On the other hand, it tells nothing about the internal stability situation in the receiving-end system, which, although entirely satisfactory while operating alone, may be changed by the presence of the transmission system. Hence, if any doubt exists as to the internal stability, it may be necessary also to give attention

1. See bibliography at end of paper for all numbered references.

to this part of the problem. In general, however, when additional power is brought into a load area from a distance, the transmission system definitely represents the weakest link. The analysis, therefore, quite frequently is limited to an examination of its performance with respect to the receiving-end system taken as a whole.

The main inconvenience in using receiving-system characteristics in the manner just described is that they have to be recalculated perhaps several times when the actual power limit is to be ascertained. This inconvenience, however, may be avoided by a modification. Instead of using a single set of receiving-end system characteristics at the junction point, a segregation of the receiving-end system into 2 parts at this point may be made.[1] These 2 parts represent an *equivalent generator* and an *equivalent load*, respectively. The generator characteristics may, or may not, include a part of the load effects within the receiving-end system.

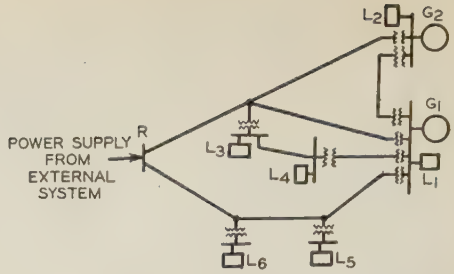
In using this type of receiving-end system representation, the load increments required for the purpose of recalculation in order to determine the power limit, may be applied to the equivalent load directly. Hence, having once determined the equivalent-generator and load characteristics, no complete revamping of the receiving-end system characteristics is necessary, as in the previous case. Therefore, using the approximate representation, the problem reduces to the handling of a 2-generator system with the load connected at the terminals of one of the generators. It should be definitely borne in mind, of course, that *this method is inherently approximate*. Nevertheless, if proper judgment be used in segregating the receiving-end system into 2 parts, and in assigning the appropriate characteristics to each, fairly reliable results may be obtained. That this method involves considerable saving in time and labor is evident.

## System Loads

The loads of an alternating current system in general may be subdivided into 4 types: (1) lighting load, (2) synchronous motor load, (3) synchronous converter load, and (4) induction motor load. The loads usually receive power over the distribution network through distribution transformers. The distribution network is connected to the substations which in turn are supplied from the generating stations over overhead or underground transmission lines or feeders. In stability investigations it is *impracticable to include all individual loads properly in the analysis*, and still it is *important to introduce at least the approximate effect of the load action.* Practically this may be done by (1) considering the load concentrated at the substations, or (2) representing the entire power system in the load area by an equivalent load of appropriate characteristics.

In the former case the characteristics of the composite load at the substation must be introduced. Two methods are here possible namely (1) the approximate method of simulating the substation loads by constant impedances, and (2) the determination and use of actual load characteristics at the substations.

**Fig. 1. Typical receiving - end system**




Load characteristics in general are given best by curves of active and reactive power versus voltage.[1,2,4] In some instances it may be sufficient to represent the load by its power factor characteristic, i. e., a curve of power factor versus voltage.

Should any of the loads include synchronous machines of sufficiently large rating to justify their identity being preserved and their being treated as separate sychronous machine units, this, of course, can be done. Whether or not this is necessary and desirable must evidently be left to the discretion and judgment of the engineer who handles the problem.

## Characteristics of Substation Loads

The loads on the substations in a power system may consist of the 4 individual types discussed in preceding paragraphs. In addition, the substations will also carry the active and reactive power losses in the distribution network caused by the various individual load currents. The segregation between different types at each substation evidently depends upon each specific situation. The composite characteristics at the substations may be approximately as indicated in Fig. 12. It is inevitable that for a commercial load the power will decrease somewhat with a drop in voltage and the reactive power will change somewhat in a leading direction.

In determining the substation loads and their characteristics it may be possible to figure back from the individual loads, including at each voltage the power and reactive power losses in the distribution system. However, this complete procedure seldom is followed, and, furthermore, sufficient detailed data frequently will not be available for such an analysis. Usually the power and reactive power at the substation itself is specified or estimated. The percentage of each type of load supplied is also specified or estimated. With this information at hand and using suitable characteristics for the variation in power and reactive power for each individual type of load, the required composite characteristics are made up. The fact that such characteristics are applied at the substations instead of at the individual loads makes very little difference. The uncertain factors and unknown quantities are so many that the inclusion of distribution losses in applying these characteristics will not affect the true result materially.

Sometimes the substation loads are represented merely by constant impedances. Although this may be very convenient from the standpoint of computation, it evidently is an approximation only. In general, constant impedance loads will have neither the correct power nor reactive power characteristics

fully to represent the actual load at all voltages. Only at the value of voltage at which the impedances are determined (usually the normal value) will the representation be exact.

### Receiving-End Systems and Their Simplification

For the purpose of the subsequent discussion a *receiving-end* system will be defined as a *compound power system to which power and reactive power are supplied at some point.* It includes, in other words, everything, i. e., machines, transformers, transmission and distribution circuits, and loads located beyond the point in question. The agent supplying power and reactive power to the point may be a generator, a transmission line, or even another power system; in the majority of instances where stability is involved it represents a transmission line fed from a distant station, as already outlined.

For purposes of analysis it is frequently desirable to simplify the receiving-end system as much as practicable. How much can be accomplished in this regard depends upon the actual layout at hand. Every system offers its own problems. Simplification by analytical methods usually involves repeated application of Y-Δ and Δ-Y transformations as well as the more general star-mesh transformations.

When the substation loads are represented by their true characteristics it is usually necessary to retain the substations as definite identities. Only when the loads are represented by impedances can they be treated as network elements proper and be included directly in the process of simplification. In such cases the result is likely to be a system considerably less complicated than when the identity of the substations is retained.

Consider the system in Fig. 1, for instance, representing a receiving-end system with respect to the point *R*. It involves, as may be seen, 2 generating stations and several substations. If the proper characteristics of the loads at the latter are included, no further simplification of this system is practicable. (The Δ-loop 1-2-3, of course, may be replaced by a "Y," but this does not involve any real simplification.) If, on the other hand, the substation loads are considered as impedances, further simplification is possible as suggested in the steps (*a*) to (*g*) in Fig. 2. These steps involve nothing but Δ-Y and Y-Δ transformations. If the distributed constants of the lines are taken into account these may be represented by their proper equivalent $\pi$ circuits. The presence of the leaks will not prevent simplification from being carried out.

Should the receiving-end system contain only one generating station and, in addition, the substation loads be considered as impedances, it may in general be represented by a single $\pi$ circuit. Referring to the previous example, Fig. 2, for instance, and considering the generators in station 2 to be removed so as to convert it into a substation, it is evident that by the simplifying steps suggested in that figure the final representation becomes an equivalent $\pi$ circuit as given in Fig. 3.

### Characteristics of a Receiving-End System

As already stated, it is frequently desirable in connection with stability analyses to represent the receiving-end system by its proper characteristics. Such characteristics in general are curves of active versus reactive power for various values of voltage at the point in question. They should include the effects of all generators in the receiving-end system, all transmission and distribution circuits, transformers, substations, and loads. From the standpoint of steady state stability calculations, the characteristics should be for appropriate constant field currents in the synchronous machines and with appropriate fixed angular displacements between these machines. To calculate these characteristics for a practical power system in many instances may be exceedingly complicated. (The consideration of fixed angular relationships is an *assumption* that governs the active and reactive power distribution among the synchronous machines within the receiving-end system. There are, however, also other bases that may be used for this purpose. See, for instance, the paper, "Power Limits of Synchronous Machines," by Edith Clarke and R. G. Lorraine in Electrical Engineering, November 1933, p. 780–7, and particularly the discussions of it in Electrical Engineering, March 1934, p. 475–7, some of which point out possibilities in this respect.)

If the substation loads are to be represented by constant impedances, the first step would be to simplify the receiving-end system as much as practicable, retaining, of course, the identity of the generating stations. Using the simplified circuit layout, expressions for power and reactive power at the point in question may be established. Equations of the type that would be applicable are developed in the literature in several places. Having these equations and using the appropriate excitation voltages and displacements between synchronous machines, the power and reactive power at the point in question

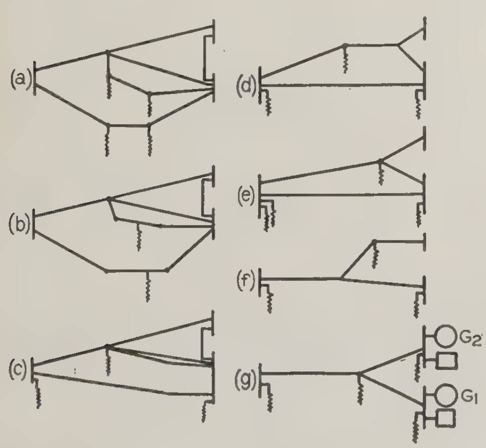



Fig. 2. Simplification of system in Fig. 1 when loads are considered as constant impedances

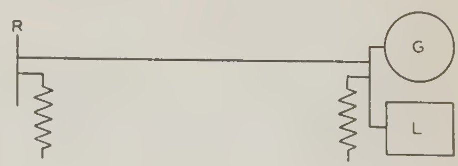



Fig. 3. Further simplification of system in Fig. 1 when generators $G_2$ are omitted

may be calculated as a function of voltage at that point. Evidently such calculations are possible only when no saturation effects are included. In other words, all circuit elements involved must be linear.

When the proper characteristics of the substation loads are to be used, the problem becomes still more involved and calculations may be so complicated as to be almost prohibitive. It is usually necessary to resort to cut-and-try methods, which evidently also allow saturation to be taken into account in the synchronous machines if desired. If the layout is not too involved it may also be possible to resort to graphical methods. In this case charts must be available for the machines as well as for the various transmission circuits. A system of superposition at junction points is used, and in this manner the nonlinear elements can be brought properly into the picture. It is evidently of no moment to attempt giving specific directions as each individual problem requires its own particular method of attack.

By far the best way of obtaining the characteristics of a complicated power system (receiving-end system) is by the use of a network analyzer (alternating current calculating table). On such an analyzer a true replica of the network can be set up, including synchronous machines and loads. The procedure evidently would be first to adjust the miniature system for conditions of normal operation. This involves adjusting for correct voltages at all buses, the proper field current as well as phase displacement of the synchronous machines, and the proper admittances representing the loads at the substation buses. Holding the field currents in the synchronous machines and the displacement angles between them constant, and a fixed voltage at the receiving-end bus, the phase angle of the latter may be changed. A change in the angle of this voltage will evidently alter the voltage at the substation buses, which in turn requires a new load admittance to be used. By a few trials the correct value of admittance corresponding to the voltage may be obtained. When everything is properly adjusted the power and reactive power at the receiving bus are determined. Proceeding in this manner, enough values for one particular voltage at the receiving-end bus are obtained so that a curve may be plotted. The magnitude of the voltage at the receiving-end bus then is changed to the next desired value and the procedure just outlined is repeated. The correct power and reactive power characteristics at the receiving-end bus are thus eventually obtained.

Characteristics of the receiving-end system indicated in Fig. 5 are given in Figs. 13 to 16. They were obtained on the network analyzer at the Massachusetts Institute of Technology, further details being given in a later section of the paper.

### Representation of Receiving System by Equivalent Load and Equivalent Generating Station

It is evident from the foregoing that to obtain the characteristics of a receiving-end system is a rather complicated, laborious, and difficult task, except when a network analyzer is resorted to. Furthermore, as already pointed out, it is usually necessary during a stability analysis to secure such receiving-end characteristics for several load conditions for the purpose of eventually determining the power limits. Hence it would be decidedly helpful to have methods available embodying *simplified equivalent representations* of the receiving-end system. The requirements of such methods are evidently that they be time and labor saving and give results that are correct to engineering accuracy. Such methods, involving a certain degree of approximation, have a further justification in that so many factors, as already pointed out, are somewhat uncertain in stability analyses of large power systems, so that undue refinements are not frequently called for.

The most drastic approximation of a receiving-end system involves the location of an *equivalent generator* and an *equivalent load* directly at the receiving-end bus, as indicated in Fig. 4. The requirements are that the equivalent generator and the equivalent load give sufficiently nearly the same operating characteristics at the receiving-end bus as the actual system.

### Equivalent Generator

The size of the equivalent generator is determined from the consideration that the short-circuit kilovoltamperes that it would supply to a symmetrical 3-phase short circuit at its terminals are the same that the receiving-end system would supply to a similar short circuit at the receiving-end bus. It is necessary, therefore, to determine the short-circuit

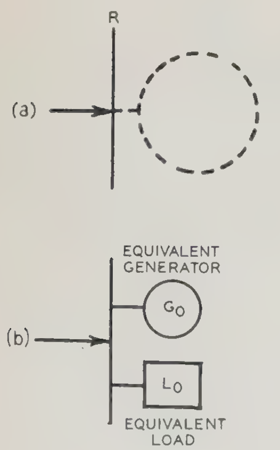
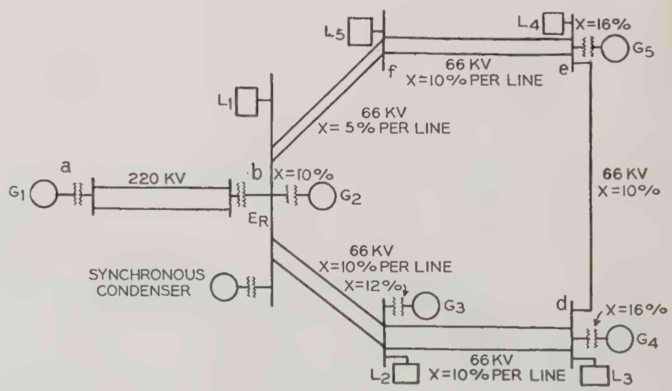



**Fig. 4 (left). Receiving-end system and its equivalent representation**

(a): Large system containing several generating stations, substations, and loads

(b): Equivalent representation of (a)

**Fig. 5 (right). Diagram of system investigated; reactances are on a 100,000-kva base**



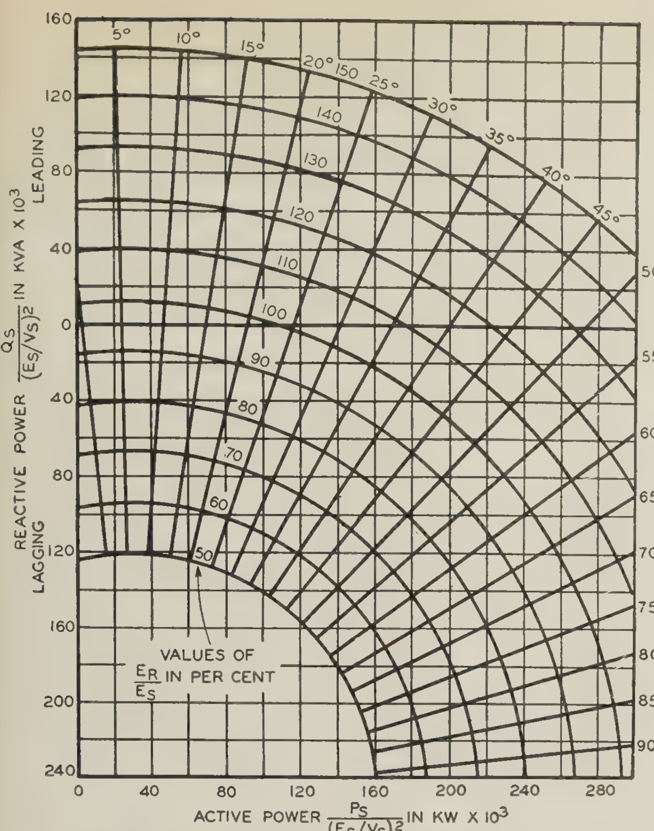



**Fig. 6. Transmission line sending chart**

Circles give ratio of receiving voltage to sending voltage. Angle lines give displacement between sending voltage and receiving voltage. $V_S$ is nominal value of sending voltage

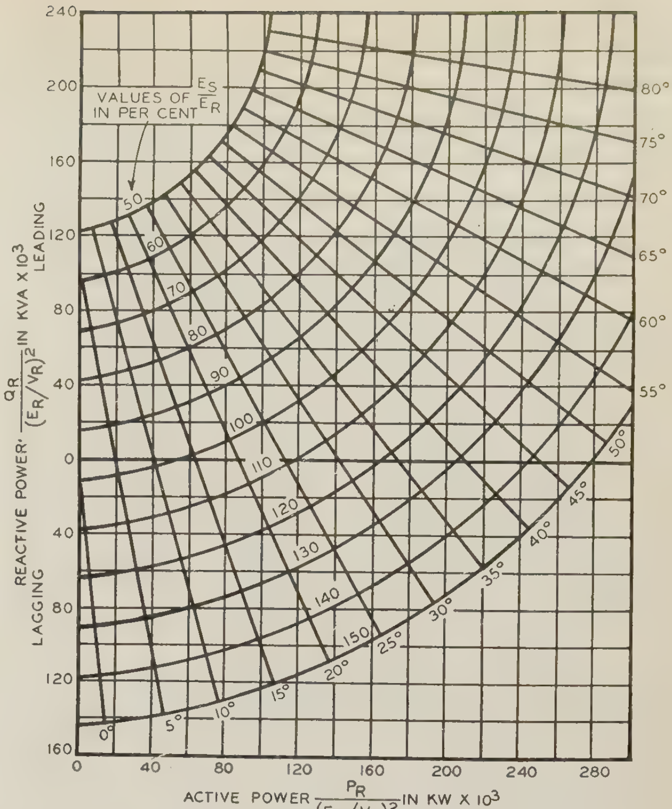



**Fig. 7. Transmission line receiving chart**

Circles give ratio of sending voltage to receiving voltage. Angle lines give displacement between sending voltage and receiving voltage. $V_R$ is nominal value of receiving voltage

kilovoltamperes of the receiving-end system. This may be done on several bases of which the following 3 are the most important ones: (*a*) with the excitation voltages of all generators phase-displaced by the proper amount and having the proper values to supply the loads on the system, and with the loads attached; (*b*) with the excitation voltages of all generators in phase but equal to their actual values with load on the system, without, however, considering the load in obtaining the short-circuit kilovoltamperes; and (*c*) with the excitation voltages of all generators in phase and equal to unity, and omitting the loads on the system.

It is evident that the first method is the correct one. It is also the one that is the most complicated, however, especially if the results are to be obtained by calculation. If the load characteristics are to be included properly this involves a cut-and-try process of calculation. On a network analyzer, however, the characteristics can be obtained without difficulty.

The second method involves an approximation. If saturation is taken into account, this method also would involve a cut-and-try process unless graphical schemes could be employed. If, on the other hand, saturation is neglected, the characteristics may be calculated by means of the input equations to a general, linear network. These may be simplified since the excitation voltages are all in phase.

The last mentioned method involves a further approximation in that all excitation voltages are considered equal to unity. Ignoring the saturation, the system in this case may be reduced drastically. As a matter of fact, independent of the number of generating stations, the result will be a circuit fed from a single station. If line admittances are to be taken into account this circuit will be an equivalent $\pi$. If line admittances are neglected, it becomes a simple impedance only. Evidently there is not much sense in including line admittances when the loads are ignored. Furthermore, since the circuit resistances have only a very minor effect on the short-circuit kilovoltamperes, a reactance system only may be used in the calculations with sufficiently accurate results.

From the values of the short-circuit kilovoltamperes the size of the equivalent generator to be attached at the receiving-end bus may be determined. The usual practice is to give this machine more or less normal generator characteristics. Since, as a rule, the machines in a receiving-end system are turbogenerators it is logical to assign unity short-circuit ratio to the equivalent machine. On this basis its size directly equals the short-circuit kilovoltamperes when the latter are determined by method *c* assuming unity excitation voltages. If another ratio is to be used the rating ($G_0$) of the equivalent machine is calculated by

$$G_0 = \frac{P}{SCR} = PX_0 \qquad (1)$$

where $P$ represents the short-circuit kilovoltamperes supplied by the receiving-end system, $SCR$ the short-

circuit ratio, and $X_0$ the unsaturated synchronous reactance in per unit.

When the excitation voltages in the actual generators have their proper load condition values, as in methods *a* and *b*, it is logical also to consider

**Table I—Station Ratings and Outputs**

All reactive kilovoltamperes are lagging

| Generating Station | Rating in Kva | Station Outputs at Normal Voltage: 1st Step | 2d Step | 3d Step | 4th Step |
|---|---|---|---|---|---|
| $G_2$ | 100,000 | 48,000 kw | 48,000 | 48,000 | 48,000 |
| | | 51,500 R. kva | 58,500 | 58,000 | 58,500 |
| $G_3$ | 75,000 | 54,000 kw | 54,000 | 54,000 | 54,000 |
| | | 41,800 R. kva | 49,300 | 49,300 | 49,300 |
| $G_4$ | 60,000 | 42,000 kw | 42,000 | 42,000 | 42,000 |
| | | 25,000 R. kva | 43,000 | 43,000 | 43,000 |
| $G_5$ | 60,000 | 42,000 kw | 42,000 | 42,000 | 42,000 |
| | | 25,000 R. kva | 43,000 | 43,000 | 43,000 |
| Transmission | | 153,000 kw | 212,000 | 263,000 | 284,000 |
| system | | 65,000 R. kva | 58,000 | 86,000 | 98,400 |

**Table II—Power Taken by Substation Loads**

| Load | Power Taken at Normal Voltage, Kw: 1st Step | 2d Step | 3d Step | 4th Step |
|---|---|---|---|---|
| $L_1$ | 100,000 | 120,000 | 133,000 | 140,000 |
| $L_2$ | 75,000 | 90,000 | 99,700 | 105,000 |
| $L_3$ | 40,000 | 48,000 | 53,200 | 56,000 |
| $L_4$ | 40,000 | 48,000 | 53,200 | 56,000 |
| $L_5$ | 75,000 | 90,000 | 99,700 | 105,000 |

the excitation voltage of the equivalent generator different from unity. It may appropriately be taken equal to its value under equivalent load conditions. Even on the basis of unity short-circuit ratio the rating of the equivalent machine then no longer coincides with the short-circuit kilovoltamperes, and is in general obtained from

$$G_0 = \frac{P}{SCR \times E_0} = \frac{PX_0}{E_0} \tag{2}$$

where $E_0$ represents its excitation voltage. Since this depends on the current supplied by the equivalent generator to the equivalent load ($L_0$) and this load in turn upon the rating of the generator ($G_0$), the calculation of the rating involves a cut-and-try process. This may be carried out as follows: Determine an approximate rating by evaluating eq 2, letting the excitation voltage be unity or equal to an assumed, reasonable value. With this rating determine the equivalent load, as discussed later, by means of eq 5, and from this the part of the load current supplied by the equivalent generator. Then

$$E_0 = E_R + jX_0I_0 \tag{3}$$

where $E_R$ is the voltage of the receiving-end bus taken at its normal value (usually 100 per cent) and $I_0$ the generator current.

Using this improved value of excitation voltage, the rating of the equivalent generator is recalculated. This again leads to new and more nearly correct values of equivalent load, generator current, and excitation voltage. This process is repeated until the correct rating has been determined.

In graphical analyses the performance of the equivalent machine may be given by charts of the type used to represent actual generators.

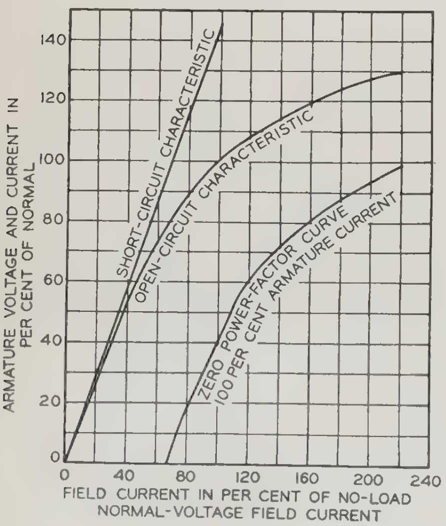



**Fig. 8. Characteristics of salient pole generators**

Short-circuit ratio, 1.46. Ratio of pole arc to pole pitch, 0.67

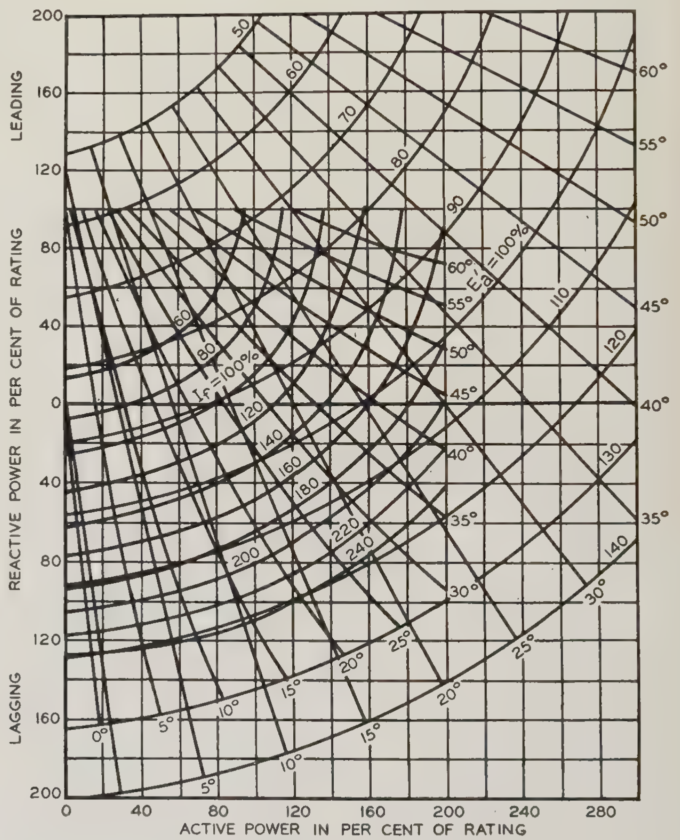



**Fig. 9. Chart for a salient pole generator at 85 per cent terminal voltage**

Circles represent voltage induced by air-gap flux in per cent of normal terminal voltage. Curves represent field current in per cent of field current at normal open-circuit voltage. Straight angle lines represent displacement in electrical degrees between voltage induced by air-gap flux and terminal voltage. Curved angle lines represent displacement in electrical degrees between excitation voltage and terminal voltage

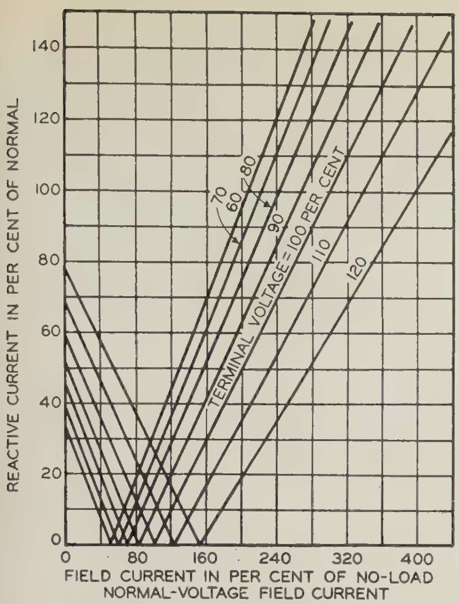



**Fig. 10 (left). Synchronous condenser V-curves**

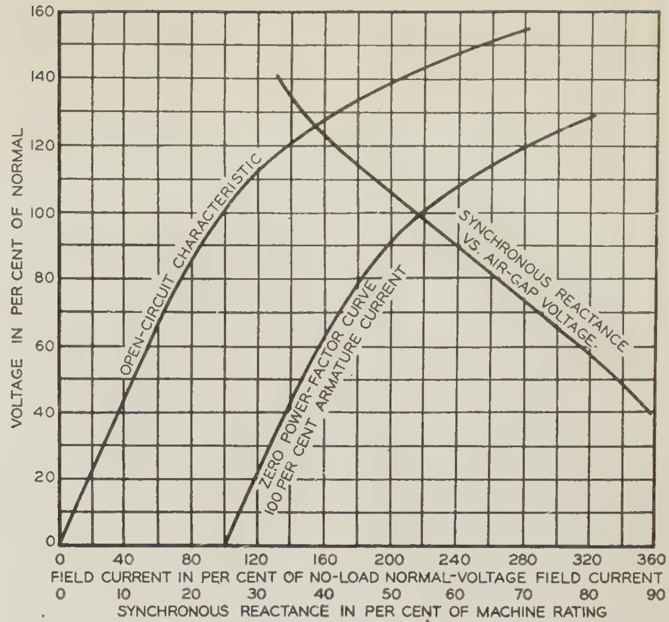



**Fig. 11 (right). Characteristics of receiving-end system turboalternators**

## Equivalent Loads

The total active and reactive power supplied to a system includes the actual loads and all appropriate transformer, distribution, and transmission losses (power and reactive-power losses). The equivalent load representing the load action of the receiving-end system may be considered equal to the total power and reactive power so supplied multiplied by a reduction factor. This reduction factor may be taken as the ratio of the kilovoltampere capacity of the generating equipment outside of the receiving-end system (assuming that all power is transmitted into the latter) and the equivalent generator to the actual total kilovoltampere generator capacity in the system as a whole (including, of course, the capacity outside as well as inside the receiving-end system).

Assume, for instance, that a hydroelectric-station of capacity $G_1$ supplies power over a transmission line to a large receiving-end system containing 3 generating stations of capacity $G_2$, $G_3$, and $G_4$. The capacity of the equivalent station is $G_0$. Let the total power and reactive power supplied to the receiving-end system be $L$. The size of the equivalent load $L_0$ is then given by

$$L_0 = L\frac{G_1 + G_0}{\Sigma G} \tag{4}$$

where the aggregate generating capacity $\Sigma G$ is represented by

$$\Sigma G = G_1 + G_2 + G_3 + G_4 \tag{5}$$

In order to obtain the total power $L$ actually supplied, it is necessary to perform several calculations starting at the actual loads of the system, or at least at the loads on the substations. Also it is necessary to know the relationship between the power and reactive power in the load $L$ and the voltage at the receiving-end bus. The same power and reactive-power variation then may be assigned to the equivalent load. Evidently this relationship cannot be determined accurately without a large amount of time and labor, since it would be necessary for accurate analysis to apply the load characteristics directly at every individual load actually on the system. Such a procedure, as previously pointed out, is prohibitive. It is considered sufficiently accurate for the approximate representation to apply individual load characteristics for different types of loads to the aggregate amount of these loads on the system as a whole. Hence, knowing the total power and reactive power of the various types of loads on the system, and having segregated out the distribution, transmission, and transformer losses at normal voltage, the load power and reactive power as well as the losses at reduced voltages may be estimated and the total power and reactive-power characteristics determined in that manner.

## Comparative Analyses

*System Used.* Figure 5 is a diagram of the specific system used in examining the approximate method of receiving-end system representation. Sending and receiving charts[1,5,6] for one circuit of the section *a-b*, comprising a 142-mile, 2-circuit, 795,000-cir mil

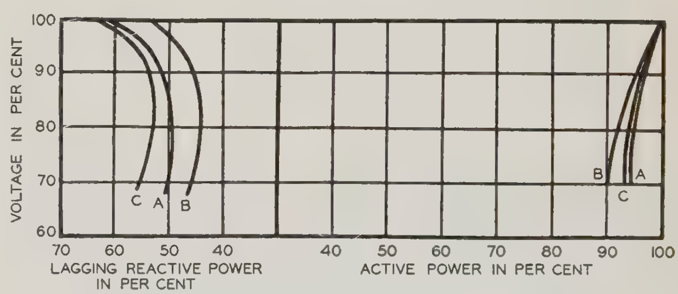



**Fig. 12. Composite load characteristics**

A: Characteristics for loads $L_1$, $L_2$, and $L_5$
B: Characteristics for loads $L_3$ and $L_4$
C: Weighted Average of A and B plus losses in 66-kv lines and transformers (used in approximate set-up)
Active power at normal (100 per cent) voltage is base for per cent active and reactive power

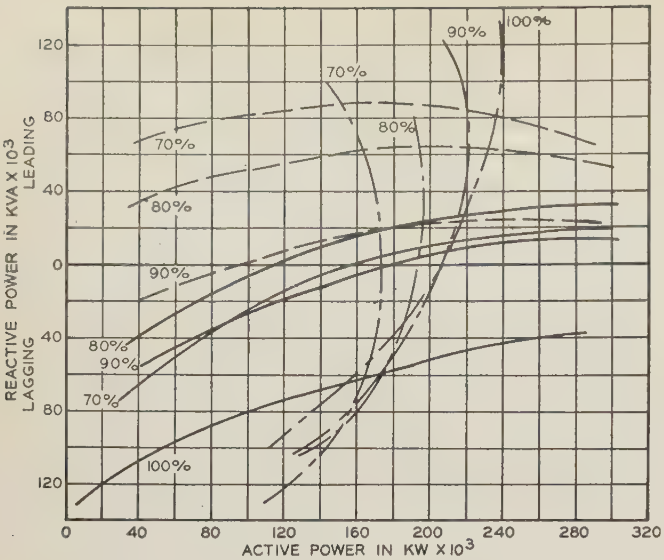



Fig. 13. Superposition of receiving-end system characteristics and transmitting-ability curves for first load condition; for identity of curves, see Fig. 14

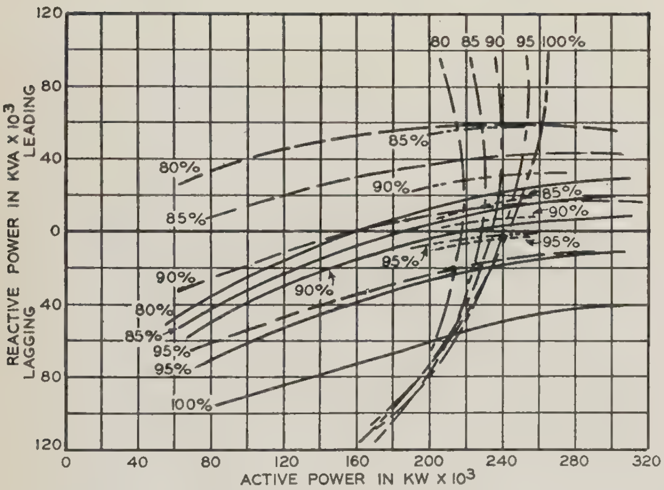



Fig. 14. Superposition of receiving-end system characteristics and transmitting-ability curves for second load condition

Solid lines: Receiving-end system characteristics for exact set-up using load characteristics
Dashes: Same with constant-impedance loads
Dots: Receiving-end system characteristics for approximate set-up using load characteristics
Dash and 2 dots: Same with constant-impedance loads
Dash and dot: Transmitting-ability curves for transmission system
Percentages on the respective curves give values of $E_R$ in per cent for those curves

A.C.S.R. line having 22.5-ft horizontal spacing and with its associated transformers, are given in Figs. 6 and 7. The constants for the other lines and transformers are given in Fig. 5, resistance, capacitance, and leakance being neglected there.

Generating equipment in hydroelectric station $G_1$ consists of 7 37,500-kva 13,800-volt 60-cycle, 150-rpm generators to which the characteristics of Fig. 8 apply. Performance charts[1,6] for these generators, of which Fig. 9 is typical, were constructed for terminal voltages between 100 per cent and 70 per cent. Synchronous condensers of capacity totaling 125,000 kva and with characteristics given in Fig. 10 are connected at the receiving-end bus *b*. Terminal voltages on these *V*-curves refer to the high-voltage side of the condenser transformers. In receiving-end generating stations $G_2$ to $G_5$ are located turboalternators with characteristics shown in Fig. 11. Values of the kilovoltampere capacities in these stations are given in Table I.

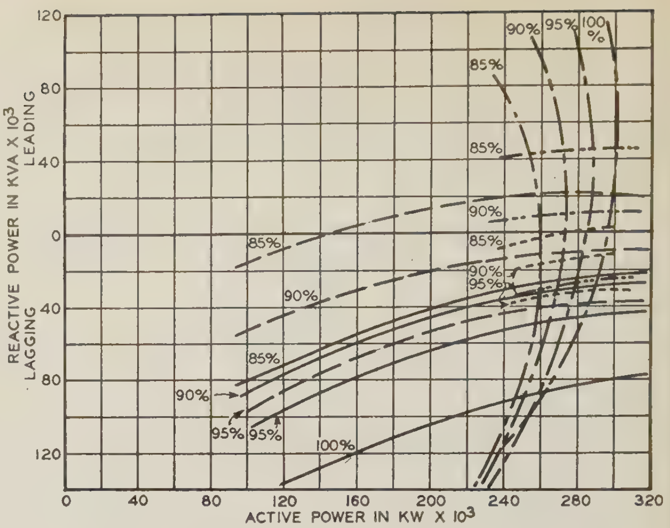



Fig. 15. Superposition of receiving-end system characteristics and transmitting-ability curves for third load condition; for identity of curves, see Fig. 14

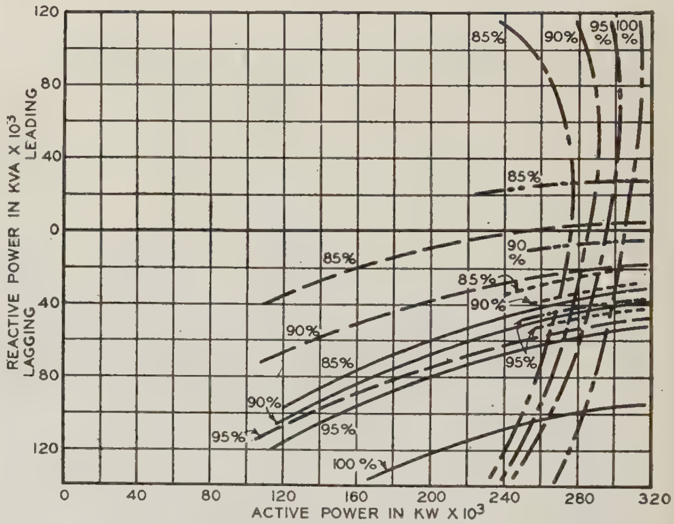



Fig. 16. Superposition of receiving-end system characteristics and transmitting-ability curves for fourth load condition; for identity of curves, see Fig. 14

The connected substation loads $L_1$, $L_2$, and $L_5$ are 60 per cent induction motors, 20 per cent synchronous motors, and 20 per cent lighting and heating; $L_3$ and $L_4$ are 50 per cent induction motors, 20 per cent synchronous motors, and 30 per cent lighting and heating. In addition, 10 per cent of the connected kilowatt load is added to include power lost in the distribution system, and 30 per cent of the connected kilowatt load value is taken as the reactive-power loss in distribution. (These figures are actually arbitrary since no specific distribution

system was considered in this investigation.) The composite load characteristics, Fig. 12, are based upon these assumptions, use being made of material given by Evans and Wagner[2] regarding variation of active and reactive power to synchronous and induction motors. When the power taken by the substation loads is increased during the course of the analysis, it is assumed that the incremental load has the same characteristics as the initial load, so that these curves may be used throughout. Total loads at the substations are given in Table II.

*Procedure.* In order to investigate the validity and accuracy of approximate methods of receiving-end system representation, 2 sets of stability analyses were carried out. In the first set an exact representation of the receiving-end system as it exists was used. The effect of saturation in the machines was included, and variations of the load impedances with voltage were accounted for by means of the load characteristics discussed previously in this paper. As a secondary issue here, the degree of accuracy lost by assuming constant load impedances was determined by carrying through an analysis under this assumption. In the second set the approximate representation of the receiving-end system by an equivalent generator and an equivalent load was used. The effects of saturation and load characteristics likewise were included here, and again the inaccuracy introduced by a constant impedance load assumption was investigated. The results of these 2 sets were then analyzed and compared in order to draw the desired conclusions.

*Exact Set-Up.* In order to determine the exact receiving-end system characteristics, the receiving-end system, comprising the part *b c d e f* of Fig. 5 exclusive of the synchronous condenser, was set up on the M.I.T. network analyzer.[7] On the analyzer the transmission system, comprising the hydroelectric station, line, and synchronous condenser, was simulated by an additional generator on bus *b*. Values of loads assumed at the substations for the initial step will be found in the second column of Table II. These loads were divided among the receiving-end generating stations and the transmission system in such a manner as to maintain as nearly 100 per cent voltage as possible on all buses in consideration of the ratings of the stations. The resulting outputs of the stations for the initial step are given in the third column of Table I, these figures including the reactive-power loss in the 66-kv lines and transformers.

These distributions then determine the field currents in the machines of the receiving-end system and the angular displacements between their rotors. With these quantities kept constant, it is then readily possible to obtain curves of active versus reactive power taken by the receiving-end system from the transmission system for various values of $E_R$, the voltage on bus *b*. Such receiving-end system characteristics for the initial step are shown in Fig. 13. Saturation was included by using the curve of synchronous reactance versus air-gap voltage given in Fig. 11, this curve being calculated from the open-circuit and zero-power-factor curves therein presented.

From the portion of the active and reactive load assigned to the transmission system in the foregoing division, the excitations in the synchronous condenser and hydroelectric station can be determined, it being assumed that 100 per cent voltage is maintained at each end of the line and transformers. With these excitations constant, superposition[1] of generator and line charts and synchronous condenser *V*-curves leads to curves of active versus reactive power delivered by the transmission system for various values of receiving-end voltage, $E_R$. (It also would have been possible to secure these characteristics of the transmission system by means of the network analyzer.) Such transmitting-ability curves for the initial step are given in Fig. 13. Superposition of the curves for the transmission and receiving-end systems then evidently gives the resultant power-voltage curve, Fig. 17, and the reactive power-voltage curve in Fig. 18.

Repetition of this process for increased values of loads leads to the additional characteristics of Figs. 14 to 16 and then makes possible determination of the power limit by extrapolation of the maxima of the resultant power-voltage curves, Fig. 17. Values of active and reactive power assumed at the substations for subsequent steps are given in Table II, and their divisions among the generators in Table I. In making these divisions, the incremental active power was always assigned to the transmission system. As in the first step, the reactive power was divided so as to maintain at the buses as nearly 100 per cent voltage as possible in view of the machine ratings.

*Approximate Set-Up.* For purposes of comparison, the short-circuit kilovoltamperes of the receiving-end system at the point where the transmission line ties in when a symmetrical 3-phase short circuit is

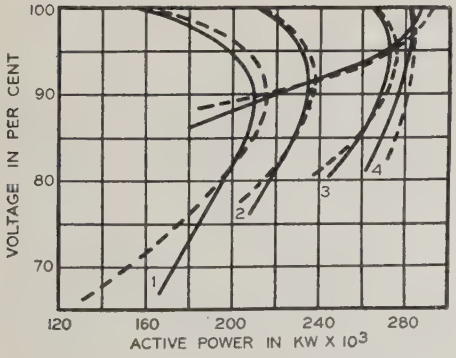



**Fig. 17 (left). Power-voltage curves from exact set-up**

**Fig. 18 (right). Reactive power-voltage curves from exact set-up**

Solid lines: Using load characteristics

Dotted lines: Using constant-impedance loads

Numbers on curves refer to steps in analysis

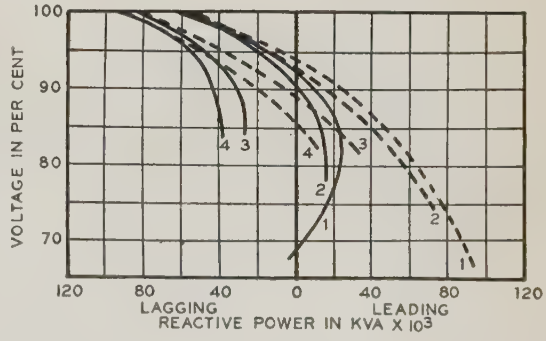


**Table III—Equivalent Generator and Load Ratings in Kilovolt-amperes and Kilowatts**

For meaning of a, b, c, 1, and 2, see text

| | a 1 | a 2 | b 1 | b 2 | c 1 | c 2 |
|---|---|---|---|---|---|---|
| Short-circuit kilovolt-amperes | 348,000 | 382,000 | 358,000 | 397,000 | 265,000 | 274,000 |
| Equivalent generator rating | 259,000 | 263,000 | 267,000 | 283,000 | 265,000 | 274,000 |
| Equivalent load rating (active power) | 371,000 | 374,000 | 377,000 | 389,000 | 376,000 | 382,000 |

**Table IV—Summary of Power Limits**

| | | Power Limit | Discrepancy |
|---|---|---|---|
| Exact method | (1) Using load characteristics | 288,000 kw | 0 |
| | (2) Using constant impedance loads | 292,000 kw | +1.4% |
| Method involving equivalent generator and load | (1) Using load characteristics | 299,000 kw | +3.8% |
| | (2) Using constant impedance loads | 315,000 kw | +9.4% |

applied at this point was found on the 3 different bases previously discussed, namely: (*a*) with the excitation voltages of all generators phase-displaced by the proper amount and having the proper values to supply the loads on the system, and with the loads attached; (*b*) with the excitation voltages of all generators in phase but equal to their actual values with load on the system; and (*c*) with the excitation voltages of all generators in phase and equal to unity. Each of the 3 cases was subdivided further by using (1) unsaturated synchronous reactances, and (2) synchronous reactances determined by the air-gap voltages from Fig. 11. The load conditions of the second step in Tables I and II were used here. The resulting short-circuit kilovolt-amperes, together with the corresponding equivalent generator and load capacities, are given in Table III. Equivalent loads in Table III correspond to the second step in Table II, the first step having been omitted in the approximate analysis.

Of these values of equivalent generator and load, the ones found by the simplest method, 265,000 kva generator and 376,000-kw load, were used in further investigations. The equivalent generator was given the same characteristics as the other receiving-end machines, Fig. 11, and the equivalent load was given a weighted average between the characteristics used previously for $L_1$, $L_2$, and $L_5$, and $L_3$ and $L_4$, with an addition to include losses in the 66-kv lines and transformers (see Fig. 12). The procedure outlined for the exact set-up was repeated to determine the receiving-end system characteristics for the equivalent generator and load. These, of course, might readily have been calculated, but the network analyzer again was used to expedite the solution. These curves for the approximate representation are plotted on Figs. 14 to 16 for superposition on the transmitting-ability curves, leading finally to the power-voltage curves of Fig. 19 and reactive power-voltage curves, Fig. 20.

## Results

Stability curves resulting from an exact determination of the receiving-end system characteristics are presented in Fig. 17. Reactive power-voltage curves likewise are presented in Fig. 18, although not required for stability and power limit determination. Two sets of these curves are given: one including the effect of the load-voltage characteristics, Fig. 12, and the other assuming loads of constant impedances fixed by the 100-per cent voltage conditions. Stability curves resulting from the approximate representation of the receiving-end system by an equivalent generator and load are shown in Figs. 19 and 20. The 2 cases involving use of load characteristics and use of the constant-impedance-load assumption also are given here. It may be noted that the capacity of equivalent generator used for these curves is that corresponding to the simplest method of determination, $c1$ in Table III.

For comparison, the power limits found by the different methods are summarized in Table IV.

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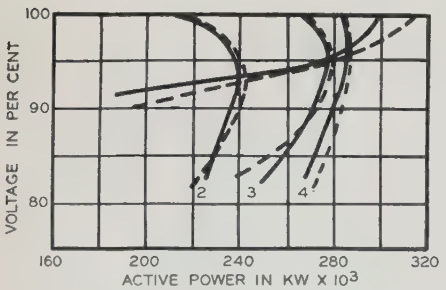
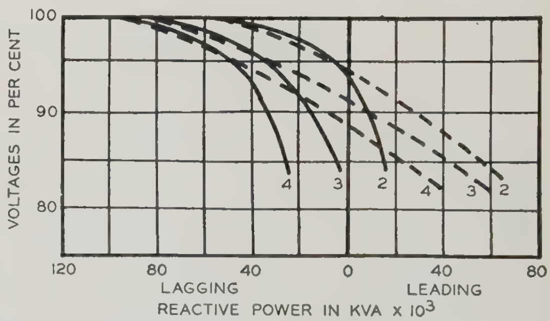



**Fig. 19 (left). Power-voltage curves from approximate set-up**

**Fig. 20 (right). Reactive power-voltage curves from approximate set-up**

Solid lines: Using load characteristics

Dotted lines: Using constant-impedance loads




Numbers on curves refer to steps in analysis; that corresponding to step 1 in Figs. 17 and 18 was omitted in the approximate set-up

# Low Pressure Gaseous Discharge Lamps—Part II

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**Radiation and conduction phenomena in low pressure gaseous discharge lamps are discussed in this paper. Part I was published in ELECTRICAL ENGINEERING for August 1934; the second and concluding part, on electrical conduction processes, is presented herewith.**

IN Part I of this paper, radiation processes in low pressure gaseous discharge lamps were discussed. In the present section, conduction processes are covered.

## Conduction Processes in Relation to Light Efficiency

To produce visible light, that is, radiation ranging from λ4,000 to λ7,000 (where λ indicates wave length in Ångstrom units, or $cm^{-8}$), requires, on the basis of eq 6 (see Part I), the impact on atoms, of electrons having kinetic energy ranging from about 3.08 to 1.76 volts. In the case of sodium, 2.1 to 3.0-volt electrons bring about excitation and emission of visible light, but in such cases as neon and mercury, the electrons must acquire a kinetic energy which is 2 to 3 volts in excess of the resonance energy, since the resonance lines of these atoms are in the ultra-violet region and visible radiations are obtained only through transitions from still higher excited states. Thus if $V_r$ denotes the resonance energy, the efficiency of light production in such cases as neon and mercury is approximately $2/(V_r + 2)$. While successive excitation does effect some saving in energy, it is evident that the efficiency of light production in sodium would be expected to be greater than that in mercury, and the latter, in turn, greater than that in neon.

The problems, therefore, of extreme importance in obtaining high light efficiency are, first, to choose the right kind of vapor or gas from the point of view of energy levels, second, to arrange the electrical conditions so that the electrons shall acquire sufficient kinetic energy to produce the maximum yield of excited atoms of the proper energy content, and, third, determine such operating conditions (pressure of gas, design of a discharge tube, etc.) that the atoms in the excited state shall give rise to the largest number of light-emitting transitions. Now the motion of any considerable number of electrons in the gas is possible only if the negative space charge that would result because of their presence is neutralized by positive ions. In fact this is the only function of positive ions in a low pressure discharge—to impart conductivity to the discharge. Furthermore, it is necessary to provide in any discharge some source of supply of electrons, and the energy thus consumed in generating electrons is therefore an "overhead" on the energy actually utilized in production of visible light.

This leads to considering in further detail the conduction phenomena in a discharge. In fact, as C. G. Found has stated,[29] "Any discussion of the production of light in a gaseous discharge must involve a consideration of such a discharge as a conductor of electricity, since the fundamental function of the applied voltage is to establish the passage of current. Any light produced is merely incidental to and a by-product of the processes which render the tube conducting."

## Cold Cathode Positive Column Discharge

Let us consider the phenomena in a long discharge tube such as those used in neon signs (Geissler tubes) and containing gas at a low pressure. When a high voltage is applied between the 2 metal disk electrodes, a discharge occurs and the distribution of light is that shown in the lower part of Fig. 8.[30–34]

The following description is taken from the paper by Langmuir and Compton.

"Figure 8 illustrates a typical discharge of this kind. Close to the surface of the cathode a glow, called the cathode glow is observed. Beyond this is the cathode or Crookes' dark space. Then comes the negative glow which is usually of considerable intensity. Passing in the direction toward the anode, the intensity of this glow gradually decreases and becomes a second dark space, called the Faraday dark space, this usually being several times wider than the cathode dark space. Then comes the positive column which begins sharply at a definite position called the 'head of the positive column.' This surface of demarcation is convex on the side toward the cathode. In most cases the positive column is of uniform intensity all the way to the anode. Sometimes, however, it is broken up into striations, which appear to consist of alternations of Faraday dark spaces and short sections of positive column. Close

Full text of Part II of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 7, 1934; released for publication July 6, 1934. *Not published in pamphlet form.*

29. *G.E. Rev.*, v. 37, 1934, p. 269–77.
30. I. Langmuir and K. T. Compton, *Rev. of Modern Physics*, v. 3, 1931, p. 191.
31. C. G. Found and J. D. Forney, A.I.E.E. Trans., v. 47, 1928, p. 747.
32. "Die Elektrischen Leuchtrohren," W. Kohler and R. Rompe. F. Vieweg and Sohn, Akt. Ges., Braunschweig, 1933.
33. "Physik der Gasentladungen," R. Seeliger. 1927.
34. "Electrical Phenomena in Gases," K. K. Darrow. The Williams and Wilkins Company, Baltimore, 1932.

to the anode, especially if this is of small size, there may be an anode glow.

"Typical phenomena such as those illustrated in Fig. 8 are usually observed most readily at gas pressures in the neighborhood of one millimeter of mercury. At any given pressure the positions of the negative glow, the Faraday dark space, and the head of the positive column are fixed with reference to the cathode. Thus, for example, if the anode is moved, these positions do not change, whereas, if the cathode is moved, these boundaries move with it. As the distance between anode and cathode decreases, the anode may reach the head of the positive column so that the positive column disappears. In a similar way, the anode can be moved through the Faraday dark space and even into the cathode dark space. If the pressure is lowered, these distances from the cathode all increase approximately inversely proportional to the pressure. Thus, with fixed distances between the electrodes, on lowering the pressure, the cathode dark space expands until it reaches the anode."

The potential distribution in such a discharge in nitrogen has been measured by C. G. Found[31] using the method of exploring electrodes as developed by I. Langmuir and H. Mott-Smith[35] and is shown in the upper part of Fig. 8. The tube diameter was 6 cm, the nitrogen pressure 0.5 mm, and the current 5 ma. The high voltage drop at the cathode is characteristic of such discharges with cold cathodes and varies from 300 or 400 volts down to as low as 60 according to the nature of the gas and composition of the cathode. There is a slight gradient in the Faraday dark space, but under certain conditions this may become zero or even negative. Throughout the positive column there is a practically constant positive gradient which we shall designate by $X$, so that the power input per unit length is given by

$$W = Xi \qquad (22)$$

where $i$ is the discharge current.

"The drop at the anode may be positive, zero, or negative, depending upon the dimensions of the anode and the current density. However, it is always small and of the order of only a few volts."[31] As will be observed from Fig. 8 a considerable fraction of the total voltage drop between the electrodes occurs at the cathode. If we denote this cathode fall by $V_c$, the power $V_c i$ is evidently not available for the production of light. K. T. Compton and P. M. Morse[36] have developed a theory in explanation of this cathode fall by assuming that the drop is utilized in accelerating positive ions which liberate electrons from the cathode by a process of bombardment. Furthermore, the electrons thus emitted acquire sufficient energy near the cathode to ionize atoms and thus provide the ions needed for bombardment. The number of ionizing collisions made in this manner by an electron in passing through the cathode fall region is of the order of $V_c/V_i$, that is, usually of the order of 10. According to the theory of Compton and Morse, practically all the current at the surface of the cathode is carried by positive ions.

35. *G.E. Rev.*, v. 27, 1924, p. 449, 538, 616, 762, 810.
36. *Phys. Rev.*, v. 30, 1927, p. 305.

The fact that the gradient in the positive column is constant leads to the conclusion that the total charge density in this region is zero, that is, the concentration of electrons ($n_e$) must be equal, or approximately so, to that of positive ions ($n_p$). That the light produced in the column is all due to excitation and not to recombination of ions and electrons is concluded not only on the basis of measurements of electron velocities, as discussed below, but also from the fact that "Electron and ion concentrations are

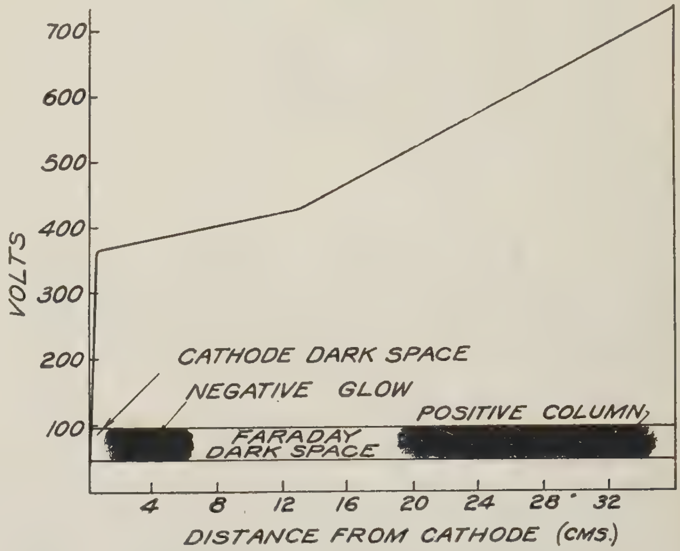



**Fig. 8. Distribution of potential in positive column discharge in nitrogen (Found and Forney)**

each of the order of 100 times larger in the negative glow than in the positive column, and their velocities are lower. If light in both regions were due to recombination, it should be $(100)^2$ times more intense in the negative glow because of greater concentrations, and still more than this because of lower velocities which favor recombination. Thus, certainly, recombination plays a negligible rôle in the production of light in the positive column."[37]

Evidence for this point of view is also furnished by the observations on the light emission from a negative glow lamp. This may be defined as a Geissler discharge in which the positive column has been completely eliminated, that is, a discharge consisting only of a cathode fall region. The light from this source is practically all due to recombination and is obviously quite low in intensity.

## Advantages of Hot Cathodes in Gas Discharges

The disadvantages in the use of cold cathodes have been presented by Found and Forney[38] in the following remarks.

"In a tube with cold cathode, the positive ions strike the cathode with a high velocity due to the high cathode drop, and cause a mechanical disintegration of the cathode. The cathodic sputtering causes a blackening of the tube walls. Another re-

37. K. T. Compton and I. Langmuir, *Rev. of Modern Physics*, v. 2, 1930, p. 123.
38. A.I.E.E. Trans., v. 47, 1928, p. 747–52.

sult of the high cathode drop is a clean-up of the gas, causing the 'resistance' of the tube to increase as the tube is operated. Also, there is a large consumption of energy at the cathode which yields no light and greatly decreases the efficiency. To avoid this large energy loss and consequent heating effect, and in order to decrease the amount of sputtering, the current density at the cathode of a Geissler tube has usually been chosen at about 10 ma per square centimeter.

"Thus we may summarize the effects of the high cathode drop as follows.

"1. It is impossible to construct a low voltage tube.

"2. In order to have good light efficiency, it is necessary to make long tubes in which the ratio of cathode drop to total voltage is decreased.

"3. There is a 'clean up' or disappearance of the gas. This may occur from other causes also, but is certainly increased due to the high cathode drop.

"4. Blackening of the tube is caused by cathodic sputtering, and in order to keep this low, there is a limit to the current density at the electrodes."

If the cold cathode is replaced by a hot cathode capable of emitting electrons in sufficient numbers to supply the discharge current, the cathode drop $V_c$ is reduced to a value which is only slightly in excess of the ionizing potential of the gas and which, in consequence of cumulative ionization, may be as low as the resonance potential. Since $V_i$ has the highest value, 24.5 volts for helium, $V_c$ need never exceed 25 volts. As mentioned in Part I, the probability of ionization is given by eq 10 and in this case the resulting form is

$$P_i \doteq C(V_c - V_i) \tag{23}$$

As a result, it is possible to obtain a sufficient density of ions near the cathode to permit the desired arc current to pass without the necessity of increasing $V_c$ to any considerable extent. C. G. Found has shown in a recent paper[39] that the possibility of drawing large electron currents from a hot cathode in an arc is due to the production of a field at the cathode by the positive ions. This field emission may be as much as 10 times the zero-field emission and evidently increases with $V_c$. No sputtering occurs if, as has been shown by A. W. Hull,[40] $V_c$ is maintained below a critical value which varies with both the nature of the cathode and the composition of the gas. For thoriated tungsten this "disintegration voltage" is about 27 with neon ions and 17 volts with mercury ions, and with all types of cathodes this voltage is always sufficiently above $V_i$ to secure a practical operating range.[41]

A number of constructions of thermionic cathodes for use in gas discharges have been described by Hull and other investigators.[42] Besides the filamentary type, inside coated cathodes with barium oxide-strontium oxide as active material are used to secure high efficiency of electron emission, and shields are often added to reduce heat losses. It is thus possible to operate oxide coated cathodes in gas discharges at emission efficiencies which are considerably greater than those obtained in vacuum devices.

Since in the following discussion only discharge tubes in which hot cathodes are used will be considered, the classification of these tubes suggested by C. G. Found[43] will be adopted. He classifies them according to the *geometry* of the containing vessel into 2 types: (1) cathodic, (2) positive column; and defines these as follows:

"A cathodic discharge is defined as one which is more or less bulbular in shape and in which the distance between cathode and anode is comparable to the smallest dimension of the bulb.

"A positive column is an elongated tube in which the distance between cathode and anode is several times the diameter."

In general, it may be stated that a cathodic type of discharge operates with a voltage drop which is approximately equal to $V_i$ and may be as low as $V_r$ (owing to successive impacts). A tungar rectifier is an example of such a discharge, and the more recently developed d-c low-voltage sodium lamp is another example. Such an arc may be started on a comparatively low voltage circuit (less than 110 volts) without any auxiliary voltage "kick."

In a positive column discharge the total voltage drop usually exceeds $V_i$ for the gas and while the discharge tube may be designed to operate on less than 110 volts, a starting kick or some equivalent device, such as auxiliary electrodes, is necessary. This initial high voltage is needed to overcome the negative charge on the walls which tends to prevent the flow of electrons. The low-pressure mercury vapor lamp with mercury cathode, and the hot-cathode high-current neon tubes are examples of this type of discharge. The high lumen output a-c sodium lamp developed recently for use on 6.6-amp constant current circuits[44,45] is another example. The main distinction between the 2 forms of discharge is in the fact that in the cathodic type all of the energy from the external source of supply is converted into kinetic energy of electrons at the cathode, and, consequently, there is no voltage gradient outside the region of the cathode fall, as in a positive column. In the latter, there is in addition to the cathode fall $V_c$, a drop in the rest of the tube which varies with the length, other conditions remaining constant.

## Cathode Drop

Consideration will next be given to what occurs in a cathodic type of discharge when a voltage is applied between the electrodes. The electrons emitted from the cathode produce ions either directly or by cumulative ionization and this permits more electrons to flow, thus altering the potential distribution between the electrodes until finally a stationary condition is attained in which the whole fall of potential is concentrated in a thin sheath close to the cathode. The rest of the space between the electrodes is field-free and is known as the plasma.

It has been shown by Langmuir[46] that if the arc

39. *Phys. Rev.*, v. 45, 1934, p. 526.
40. A.I.E.E. Trans., v. 47, 1928, p. 753.
41. A. W. Hull, *G.E. Rev.*, v. 32, 1929, p. 213.
42. L. J. Buttolph, Ill. Engg. Soc. *Trans.*, v. 28, 1933, p. 153.
43. *G.E. Rev.*, v. 37, 1934, p. 269–77.
44. G. R. Fonda, *G.E. Rev.*, v. 37, 1934, p. 331–7.
45. N. T. Gordon, *G.E. Rev.*, v. 37, 1934, p. 338–41.
46. *Phys. Rev.*, v. 33, 1929, p. 954.

current is less than the thermionic emission from the cathode for zero field, then the sheath is actually a double sheath consisting of an electron space charge next to the cathode and a positive ion space charge next to the plasma. Under these conditions the ratio $\gamma$ between electron current density $I_e$ and positive ion current density $I_p$ at the cathode is given by

$$\gamma = I_e/I_p = \sqrt{m_p/m_e} \qquad (24)$$

where $m_e$ and $m_p$ denote the mass of electron and positive ion, respectively. (Table VI shows values of $\gamma$ for different gases.) The voltage gradient is zero at both the cathode surface and the edge of the plasma (the writer has followed in this discussion the remarks of C. G. Found[39,43]) and the relation between $I_e$ (or $I_p$), sheath thickness $d$, and cathode fall $V_c$, is given by a space charge equation. Calculation shows that for current densities, such as are used in practical lamps, the value of $d$ is of the order of 0.01 cm, which, at one millimeter pressure, is considerably less than the mean free path of an electron, so that most of the electrons that are accelerated in the cathode sheath retain their energy when they enter the plasma. As they drift through the plasma to the anode, this energy is used up in excitation and ionization of atoms of the gas with which they collide (in the manner described in Part I).

In the plasma, the number of ions generated per second by the electron current $I_e$, is given by the relation derived from eq 23.

$$n_p/I_e = C(V_c - V_i) \qquad (25)$$

The fraction $f$ of the ions formed, which flows to the cathode, constitutes the positive ion current density $I_p$. Therefore

$$I_p = f \cdot C \cdot I_e(V_c - V_i) \qquad (26)$$

Since $f$ is determined by the geometry of the bulb and electrodes and by the extent of the region of generation of positive ions (which changes only slightly with current density) $V_c$ can be altered only by varying $\gamma$. Under the conditions specified above, that is, with the arc current less than the zero-field emission from the cathode, $\gamma$ is determined by the nature of the gas, and, therefore, $V_c - V_i$ has a definite value which may be calculated from the known values of $C$ and $\gamma$ and an experimental determination of $f$ for the particular design of discharge tube used.

In those discharges in which cumulative ionization occurs, $V_i$ is replaced by $V_m$, the excitation potential of the metastable states, and in this case also $V_c - V_m$ may be calculated by means of eq 26, using the corresponding value of $C$.

Now it may be deduced very readily that the light production will depend upon the value of $V_c - V_i$ (or $V_c - V_m$). If this is found to be considerably less than 2 volts, it is evident that the electrons which have left the cathode sheath and produced an ion or metastable state by collision with an atom, will not have sufficient energy to excite atoms to such levels as will give rise to visible light, since this latter process requires that the electrons shall have a kinetic energy between 2 and 3 volts. Consequently, with too low a value of $V_c$, the light output will be very low. That is, in order to obtain high light output from a cathodic type of discharge, $V_c - V_i$ (or $V_c - V_m$) must be of the order of 2.5 volts. Now such a result may be secured by decreasing the pressure, which decreases $C$, but obviously this involves fewer collisions and therefore low light output. Hence, to secure high light output, it is necessary to decrease the value of the ratio $\gamma = I_e/I_p$, that is, to increase the positive ion current to the cathode. This is accomplished by having the arc current exceed the zero field emission, since the excess current is then obtained by the action of the field established at the cathode by the positive ions. It is therefore evident from these considerations that in a cathodic type of discharge, the efficiency of light production is determined by the relation between arc current and zero-field emissivity of the cathode. This conclusion will be illustrated in a subsequent section by a consideration of the light producing processes in a discharge in neon and sodium.

### Primary, Secondary, and Ultimate Electrons.[47] Electron Temperature

Since, as has been mentioned already, there is only a slight probability of a collision between an electron and a gas atom in the sheath, practically all the electrons leave the sheath with the energy $V_c$. These *primary* electrons may then ionize a gas atom, and the energy $V_c - V_i$ is then distributed between the original electron and the electron liberated from the atom, which together constitute the class known as *secondary* electrons. These secondary electrons may have sufficient energy to cause one or more excitations, and when their energy is reduced to such an extent that most of them can suffer only elastic collisions they are known as *ultimate* electrons. Owing to their low velocity as compared with both primaries and secondaries they constitute the largest fraction of the electrons in the plasma.

The ultimate electrons at any point in the plasma possess a Maxwellian distribution of energies which is defined in terms of an "electron temperature," $T_e$, and the Maxwell Boltzmann equation

$$n = n_e \epsilon^{-Ve/kT_e} \qquad (27)$$

In this equation $n_e$ is the concentration of electrons per unit volume in the plasma, and $n/n_e$ is that fraction of the electrons which have an energy in excess of $V$ volts. Since $e/k = 11{,}600$ deg K per volt, we can write the last equation in the form

$$n = n_e \epsilon^{-\frac{11{,}600V}{T_e}} \qquad (28)$$

The average energy of the electrons corresponding to the temperature $T_e$ is

$$\frac{1}{2} m_e v^2 = \frac{3}{2} kT_e \qquad (29)$$

Since the electrons move in the plasma in random directions, the random electron current density, that is, the number of electrons crossing unit area per unit time in any given direction is

$$I_e = n_e e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2}$$
$$= 2.48 \times 10^{-14} n_e \sqrt{T_e} \text{ amp/cm}^2 \qquad (30)$$

By measuring the current to a fine wire (or small disk) inserted in the plasma, as a function of the potential of the probe, it is possible to determine both $I_e$ and $T_e$, as has been shown by I. Langmuir and H. Mott-Smith.[48,49] In a cathodic type of discharge, such as that in neon at one millimeter pressure, $T_e$ for the ultimate electrons is about 5,500 deg K, that is, about 0.5 volt. Of these electrons, the fraction capable of exciting a sodium atom (2.10 volts) as calculated from the Boltzmann equation (eq 28) is $\epsilon^{-4.4}$ approximately, or about 0.012.

The positive ions in the plasma do not have a Maxwellian distribution since their motion is governed by the electric fields resulting from the variation in electron concentration in different regions of the plasma. As L. Tonks and I. Langmuir have stated,[50] the positive ions "are supposed to have negligible velocity when formed and to acquire only such velocities as correspond to the electric fields through which they pass. In the case of long mean free paths (low gas pressures) each ion will thus fall freely under the influence of the small plasma fields set up by the electrons and ions themselves until it strikes the tube wall or an electrode. For short free paths (higher gas pressures) the ion will be impeded in its motion by collision with atoms but still will be guided mainly by the electric field in which it finds itself."

In their earlier papers, Langmuir and Mott-Smith stated that the motions of the ions may be described roughly as corresponding to a temperature $T_p = T_e/2$. However, this description applied only to the measurements made with probes in positive column discharges, and cannot be valid for the ions in a cathodic discharge. In fact, as Tonks and Langmuir point out in their more recent paper,[75] "It seems entirely unreasonable that the ion energy should even approach the electron energy in view of the fact that it is the electrons primarily which supply energy to the rest of the plasma and the positive ions with their large relative mass and frequent impact with slow atoms are not adapted to acquiring large random kinetic energies."

If the positive ions had a true Maxwellian distribution corresponding to $T_e$, the ratio of electron current density $I_e$ to positive ion current density $I_p$ would be given by the relation

$$I_e/I_p = \sqrt{m_p/m_e} \tag{31}$$

which has been given in a previous section for the ratio of currents in the double sheath at a thermionic cathode. Actual observations in positive column discharges have led to the relation

$$I_e/I_p = \sqrt{m_p/2m_e} \tag{32}$$

which may be derived on the basis of theoretical considerations. Table VI gives values of $\sqrt{m_p/m_e}$ and $\sqrt{m_p/2m_e}$ for various gases which correspond to the values of $I_e/I_p$ derived by means of eqs 31 and 32. While it is certain that a similar relation cannot apply to cathodic discharges, it is evident that in this case also, the random electron current density directed toward the walls at any point must be considerably greater than the positive ion current density.

### Sheaths on Walls

The fact that the random current densities in the plasma are so different leads to the formation of sheaths on the walls and other insulated surfaces. As pointed out by Langmuir,[51] "If the glass walls of a tube containing a plasma were at the same potential as the plasma itself, the current relationship given by eq 32 shows that the walls would receive electron currents hundreds of times greater than correspond to the positive ions that reach the walls.

**Table VI—Mass Relations for Various Gases**

| Gas | $\sqrt{mp/me}$ | $\sqrt{mp/2me}$ |
|---|---|---|
| Helium (He) | 85.6 | 60.5 |
| Neon (Ne) | 192.5 | 136.1 |
| Argon (A) | 270.5 | 191.3 |
| Sodium (Na) | 205.3 | 145.2 |
| Mercury (Hg) | 605.6 | 428.3 |

Actually, in a steady state, the number of negative and positive charges which reach an insulated wall must be equal. To render these currents equal, the walls must therefore become so highly negatively charged that they force nearly all the electrons back into the plasma. The walls thus become covered with a positive ion sheath. The potential drop in this sheath can be calculated by means of the Boltzmann equation (eq 28). Since the electron temperature is uniform throughout the plasma, the current density $I_w$ which moves against the retarding field in the sheath is proportional to the electron concentration $n$ and thus eq 28 may be written

$$I_w = I_e \epsilon^{-Ve/kT_e} \tag{33a}$$

where $I_e$ = random current density in plasma."

In terms of ordinary logarithms, this equation becomes

$$2.30 \log (I_e/I_w) = \frac{11{,}600\,V_s}{T_e} \tag{33b}$$

where $V_s$ denotes the negative potential to which the walls are charged (that is, the voltage drop in the wall sheath).

The values of $I_w$ and $I_e$ may be determined experimentally by means of probe measurements, thus making it possible to calculate $V_s$. For instance, in a cathodic discharge in neon at one millimeter, if we substitute the value $T_e$ = 5,500 deg K for the ultimate electrons, and assume that $I_w = I_e/136$, it follows that $V_s$ = 2.33 volts.

### Relation Between Light Output and Current in Cathodic Discharge Lamps

In a cathodic discharge the light produced is the result of collisions between atoms in the normal or

47. I. Langmuir and H. A. Jones, *Phys. Rev.*, v. 31, 1928, p. 357.
48. *G.E. Rev.*, v. 27, 1924, p. 449, 538, 616, 762, 810.
49. I. Langmuir, Frank. Inst. *Jl.*, v. 214, 1932, p. 275.
50. *Phys. Rev.*, v. 34, 1929, p. 876.

51. Franklin Institute *Jl.*, v. 214, 1932, p. 275.

excited states with electrons which have acquired their energy in the cathode fall sheath. The extent of the light region is thus governed by the distances which the electrons traverse before their energy has decreased to such a value that they have become ultimate electrons. It is therefore a function of both gas pressure and magnitude of cathode fall $V_c$. As has been emphasized already, the function of the ions is merely to eliminate the negative space charge that would limit the arc current to a low value if electrons only were present. In consequence, the voltage drop in the arc adjusts itself to such a value for any given arc current that both a sufficiently strong field will exist at the cathode to provide the necessary electron emission and the electrons will have sufficient energy to produce the ionization required by the electron current in accordance with eq 26 and eq 24.

The relation between current and light output varies according to the nature of the processes involved in the production of the light, which, in turn, differ with both the composition of the gas and the magnitude of the cathode fall $V_c$.

Consider first a discharge in a vapor, such as that of sodium, in which the light emitted is mainly resonance radiation. If the vapor pressure is fairly high (0.01 mm or higher) and the current density not too great, $V_c$ will exceed $V_i$ by about one volt, and therefore the primary electrons will have an energy equivalent to about 6 volts. Since, as has been mentioned previously, $P_i$ increases linearly with $V$, while $P_e$ for excitation of sodium atoms to the $3P$ state passes through a maximum at about 2.5 volts (see curve in Fig. 2) and decreases slightly for larger values of $V$, it depends upon the exact value of $V_c$ as to which process will occur more frequently. Both ions and excited atoms in the $3P$ state will be produced, and the primary electrons will lose 5.1 volts in the first process and 2.5 in the second. The secondary electrons which have 0.9-volts residual energy are obviously unable to produce any further excitation and will therefore be ultimate electrons, while the electrons with 3.5-volts residual energy will be able to cause one further excitation before becoming ultimate electrons. However, as the concentration of excited atoms increases, more radiation of the $D$-lines is emitted and this is reabsorbed by normal atoms with the resulting phenomenon which has been designated in a previous section as "imprisonment of radiation." As a result the number of sodium atoms capable of being excited and ionized decreases and the light output reaches a saturation. Hence, it can be expected that the light output will increase linearly with currents for small values of the latter, but will tend to reach a constant value for higher currents.

If the pressure of sodium is low, the value of $P_i$ is decreased and $V_c$ must increase to 8 or 9 volts in order to obtain sufficient ionization. This is a direct consequence of eq 27. Under these conditions, a primary electron will still retain 2.5 volts after an ionizing collision and will thus be able to excite a sodium atom. In other words, all the electrons leaving the cathode sheath contribute toward the production of $D$-line radiation. Hence, while the intensity of this radiation increases linearly with current, as before, the efficiency of light production is much greater at the lower pressures. Also at higher currents, saturation phenomena occur as in the vapor at higher pressures.

As a matter of fact, a lamp utilizing a discharge in sodium vapor alone is possible only if some other source of energy is supplied for evaporating the sodium. Therefore, neon or argon at one millimeter pressure, or higher, is used in sodium vapor lamps to function as starting gas, and for the first few minutes (until the vapor pressure of sodium increases to about 0.0005 mm) the spectrum of the light emitted is characteristic of the rare gas. Furthermore, even when the $D$-line radiation becomes predominant, and until the pressure of sodium becomes much higher (of the order of 0.002 mm), the spectral lines of neon or argon are also emitted and the electrical characteristics of the discharge are practically the same as those in the rare gas alone.

In the case of neon at one millimeter pressure, the value of $V_c$, as observed by probe measurements, is about 18 or 19 volts under usual operating conditions and it is only when the vapor pressure of sodium increases to values above about 0.002 mm that $V_c$ decreases to about 8 or 10 volts and at the same time the neon or argon lines disappear completely. Since the maximum light output is obtained with the higher values of $V_c$, it is important to consider more fully the nature of the light producing processes in a cathodic type of discharge in neon at about 1 to 5 mm pressure, in the absence of sodium.

Owing to the fact that $V_c$ in such a discharge is less than $V_i$, the primary electrons are unable to cause ionization by direct impact, and, as a result, the neon atoms are excited to the lower resonance and metastable levels (the 4 $s$-states indicated in Fig. 5 at 16.53 to 16.77 volts). The resonance radiation emitted by the states $s_2$ and $s_4$ is very strongly absorbed by normal neon atoms, and therefore persists in the gas for very long periods. The metastable states $s_3$ and $s_5$, because of their long life, accumulate in concentration and may therefore be excited to the $p$-states by further impact from the secondary electrons which have retained (19 − 16.5 =) 2.5 volts and higher values of kinetic energy.

An electron accelerated by the cathode fall may collide with a metastable neon atom directly and ionize it. The probability of this process is much greater than that of direct excitation to a $p$-level. Since the energy required for ionization of a metastable neon atom is 21.5 − 16.5 = 5 volts, the secondary electron which results from the impact of a primary electron on a metastable neon atom with the formation of an ion, still retains 19 − 5 = 14 volts kinetic energy. It is therefore capable of ionizing 2 metastable atoms by subsequent collisions. Thus the ionization produced in a neon discharge must be of the cumulative type, and measurements with probes at different distances from the cathode, of the electron temperatures, have shown that this representation of the phenomena in such a discharge is essentially correct.

From this point of view, a discharge in neon at one millimeter pressure may be regarded as a dis-

charge with a cathode drop of 18 or 19 volts in a gas which has an ionization potential of 5 volts and a first excitation potential of about 2 volts, and it is possible to derive an approximate relation between light output and arc current, as follows:

At any current, the rate of excitation of metastable atoms to higher levels by electron impact and the rate of destruction by diffusion to the walls must be equal to the rate at which metastable atoms are formed by primary electrons. If $I$ denotes the current, and $n_m$ the concentration of metastable atoms, it readily follows that at equilibrium,

$$n_m = AI$$

where $A$ is a constant involving probabilities of excitation.

The light emitted ($L$) by any line of frequency $\nu_{km}$ is given, in accordance with the considerations presented previously, by a relation of the form

$$L_{km} = n_k \cdot h\nu_{km}/\tau_{km} \tag{34}$$

where $n_k$ is the concentration of atoms in state $k$, and $m$ is the metastable state to which the light-emitting transition occurs.

But as a first approximation,

$$n_k = BIn_m$$

since the atoms in state $k$ are produced by excitation of metastable atoms. Consequently, to a first approximation

$$L_{km} = CI^2 \tag{35}$$

That is, when cumulative ionization occurs, the light output increases with current more rapidly than when such a process does not occur. However, other processes occur by which the light output is decreased, so that eq 35 can be considered as valid only at very small current values. Thus, the excited atoms in the $p$-levels are destroyed by collisions with electrons of low kinetic energy (collisions of the second kind), and by collisions with the walls; also the rate of ionization of metastable atoms increases with the current because of increased value of $V_e$, so that the relative number which may be excited to $p$-states does not increase as rapidly. As a result the light output tends to reach a saturation value in this case also.

The mode of light production in neon at 1–5-mm pressure which contains about 0.001-mm pressure of sodium vapor may now be considered. As has been pointed out by Found,[43] "Since the pressure of neon is several thousand times that of sodium, it is extremely improbable that a sodium atom will be excited or ionized by a primary electron before the latter has lost energy to a neon atom. On the other hand, the secondary electrons are unable to cause any excitation of neon, and although they may have collided several thousand times with neon atoms before striking a sodium atom, they will still be able to excite the latter. Thus in a cathodic sodium lamp the generation of light is produced mainly by the secondary electrons and the light output determined by the number and energy of these electrons." The maximum light output will be obtained with secondary electrons of kinetic energy equivalent to 2.5 volts. Therefore, in a neon-sodium lamp, the light output is greatest when $V_e$ is slightly greater than 16.5 + 2.5 = 19 volts. These considerations thus illustrate the conclusion stated in a previous section that the thermionic characteristics of the cathode are of great importance in determining the light output and efficiency of a cathodic discharge lamp.

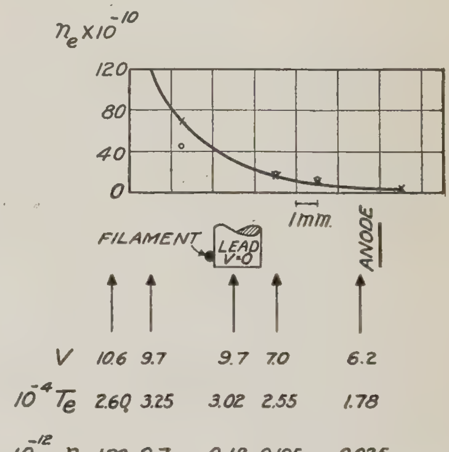
The relation between light output and current in a cathodic neon-sodium lamp at constant wattage input (to maintain constant vapor pressure of sodium) is linear over a large range of currents, as has been shown by Found.[29] It has been found that in this range the light obtained is 1,000 lumens per ampere. "This corresponds to the generation of one light quantum per primary electron. When the discharge is all sodium, the linear portion of the curve (lumens versus current) corresponds to only about 500 lumens per ampere."

## Reverse Field in Low Voltage Arcs

(A more complete presentation of this topic is given by K. K. Darrow.[52])

From the considerations in the previous sections it might be concluded that the minimum voltage drop between anode and cathode for the operation of a cathodic discharge should correspond to the resonance potential $V_r$, since obviously $V_e$ cannot be less than this value. However, it is a fact often observed with this type of discharge that the voltage drop between the electrodes may be considerably lower than $V_r$. For instance, a cathodic discharge in neon at one millimeter pressure may be obtained with an arc drop of 12 to 14 volts (whereas $V_r$ = 16.5 volts); and similar observations have been made with arcs in argon, helium, mercury, and sodium.

**Fig. 9. Distribution of potential, electron temperature, and electron concentration in low voltage arc in argon**




The explanation of this phenomenon was first obtained by K. T. Compton and C. Eckart[53] as a result of observations with a probe which could be inserted at different points between a hot cathode and anode in argon at a few millimeters pressure. In Fig. 9 is shown a typical set of data obtained for

52. "Electrical Phenomena in Gases," K. K. Darrow, p. 383–86.
53. *Phys. Rev.*, v. 25, 1925, p. 139.

$T_e$, $n_e$ and $V$, the potential shown being with respect to the cathode at the points in the plasma indicated by arrows. The scale of distance is given by the short line marked one millimeter; the observed arc drop was 5.2 volts and the arc current 0.45 amp. The value of $V_r$ for argon is 11.5 volts, and while this set of data shows a maximum potential of 10.6 volts behind the cathode; other data give values of this maximum as high as 11.6, thus showing that $V_c$ is actually about 11.5 volts, as expected, but that there is a reverse field between cathode and anode of about 6 volts, so that the actually observed arc drop is only 5.2 volts.

"The apparent difficulty," Compton and Eckart remark, "which arises from the fact that the electron current (which is practically the entire arc current) flows against an opposing field, disappears on consideration of the concentration gradient of electrons which is shown by the graph. It is obvious from general considerations based upon ionic and electronic mobilities, that this concentration gradient is the equivalent of an electromotive force. J. J. Thomson has called attention[54] to this force which is given by

$$E = \frac{\mu_- - \mu_+}{\mu_- + \mu_+} \frac{e}{kT} \log \frac{N_1}{N_2}$$

where $E$ is the potential difference set up between 2 regions of ion concentrations $N_1$ and $N_2$, $\mu_-$ and $\mu_+$ are the mobilities of electrons and positive ions, and $(3/2)kT$ is the average kinetic energy of the ions. (It is assumed that this is the same for electrons and positive ions. If this is not true, the equation is more complicated, but the underlying features are similar.)

"Usually this force has been considered as negligible in comparison with that due to the applied electric field. Under suitable conditions, however, it may become of primary importance. The favorable conditions are a long free path for the electrons and a high concentration gradient. The first of these conditions is realized to an unusual degree in argon and probably accounts in the case of this gas for the persistence of the nonoscillatory low voltage arc and the unusually large reverse field in the gas. In helium the authors have observed it only occasionally, and in mercury vapor it is also less clearly defined than in argon. In these gases the maximum observed reverse field was 3 or 4 volts. Measurements in mercury showed concentration gradients similar to those reported here for argon."

Similar observations on the existence of maxima for $V$ and $n_e$ in cathodic discharges in neon have been made by M. J. Druyvesteyn.[55] He found that while $V_c$ was as high as 19 volts, the arc drop was as low as 13 volts, which is in agreement with observations made in this laboratory on the d-c neon and sodium lamp.[45] In this case the maximum value of $n_e$ was $2.4 \times 10^{12}$, and $T_e$ decreased from about 30,900 near the cathode to about 11,500 at the anode.

These observations are thus in agreement with the views expressed in the previous section regarding cumulative ionization, and the gradual loss of energy by secondary electrons in excitation of metastable neon atoms.

54. "Conduction of Electricity through Gases," J. J. Thomson, p. 85 (1906).

### Voltage Gradient, Electron Temperatures and Concentrations in Positive Column

In a cathodic type of discharge, the electrons acquire a high kinetic energy in the cathode sheath and then lose this energy in excitation and ionization of atoms. Thus the kinetic energy decreases with increase in distance from cathode and finally when the electrons have reached the stage in which their kinetic energy is no longer adequate for excitation (ultimate electrons) the light generation also disappears.

The fact that the light generation is uniform throughout the length of the positive column shows that the electrons must acquire energy for excitation and ionization from some other source than the cathode fall. This energy is supplied, obviously, by the energy input into the column, that is, $Xi_A$ watts per unit length, where $X$ is the voltage gradient and $i_A$ the arc current. The magnitude of $X$ varies with current density and pressure of gas, as illustrated by the data in Table VII given by C. G. Found and J. D. Forney for a discharge in neon in a tube 2.55 cm diameter. It will be observed that the gradient exhibits a flat minimum between 2 and 5 mm; also that it decreases with increase in current, so that the positive column has a "negative" resistance.

According to the theoretical considerations developed by W. Schottky,[56] the gradient in a positive column discharge should vary approximately inversely as tube diameter, when current and pressure of gas are maintained constant. The larger the diameter, the smaller the relative loss of ions and electrons by diffusion to the walls, and hence the smaller the energy input to compensate for this loss of charged particles. The values of $X$ observed by Found and Forney for different diameters were found to be in satisfactory agreement with Schottky's conclusion.

According to A. Guntherschulze,[57] the observed gradients in monatomic gases may be represented as a function of the diameter $d$, by an empirical equation of the form

$$X = \frac{c}{d\left(1 + \frac{aI}{d}\right)} \tag{36}$$

where $c$ and $a$ are constants, and $I$ is the arc current. In a more recent paper by W. Elenbaas[58] it has been found that the gradient in mercury vapor at different pressures is a function of $d$ and $I$ of the form

$$X = \frac{c}{d^a I^b}$$

where $a$ and $b$ are exponents which vary with the pressure of the gas. At 100 deg C (vapor pressure of 0.276 mm) these constants have the values $a = 0.69$ and $b = 0.12$. Hence Schottky's conclusion can be regarded as only approximately valid.

Owing to the fact that the gradient in the column is constant, the net charge density must be prac-

55. *Zeit. f. Phys.*, v. 64, 1930, p. 781.
56. *Physikal. Zs.*, v. 25, 1924, p. 342, 635.
57. *Zs. f. Phys.*, v. 41, 1927, p. 718; v. 42, 1927, p. 763.
58. *Zs. f. Phys.*, v. 78, 1932, p. 603.

tically zero, as has been mentioned previously. Thus there must be some mechanism by which ions may be produced by impact of electrons on atoms, and the only method available is the impact of high-speed ultimate electrons. While the average kinetic energy of these electrons is much too low for ionization, and may even be too low for excitation, it should be observed that these electrons possess a Maxwellian distribution of energy corresponding to a temperature, $T_e$, and therefore have an average kinetic energy of $\frac{3}{2}kT_e$. At any given temperature, the number of electrons per unit volume $n$ capable of causing ionization is given, in accordance with eqs 27 and 28 by the relation

**Table VII—Variation in Voltage Gradient in Neon With Pressure and Current**

| Press. in mm | Arc amps | X volts/cm |
|---|---|---|
| 0.2 | 2.0 | 1.95 |
| 0.6 | | 1.90 |
| 1.5 | | 1.72 |
| 3.1 | | 1.65 |
| 4.25 | | 1.61 |
| 4.9 | | 1.80 |
| 0.2 | 0.5 | 2.1 |
| | 1.0 | 2.0 |
| | 2.0 | 1.95 |
| | 3.8 | 1.87 |
| | 6.8 | 1.78 |

$$\frac{n}{n_e} = \epsilon^{-V_ie/kT_e} = \epsilon^{-11{,}600\ V_i/T_e}$$

where $n_e$ is the total concentration per unit volume. Thus for a value of $T_e = 40{,}600$ (equivalent to 3.5 volts), which has been observed for a positive column discharge in neon, $V_ie/kT_e = 21.5/3.5 = 6.15$; $n/n_e = 0.0021$, while for $V = 16.5$ volts (the excitation energy for metastable atoms), the corresponding value of $n/n_e = 0.009$. At any given electron temperature there is therefore present a small concentration of electrons capable of either excitation or ionization. The energy lost by these high-speed electrons through the processes of excitation and ionization is supplied by the energy input $Xi_A$, and in this manner the Maxwellian distribution of energy among the electrons is maintained. The problem of a mechanism for this transfer of energy has been investigated by I. Langmuir[59] who concludes that probably there is an interaction of radiation with excited atoms and electrons.

From these considerations, it follows that the electron temperature is the most important factor in maintaining the ionization and excitation in the positive column. This is shown by the manner in which $T_e$, the electron temperature, varies with conditions in the discharge. The data in Table VIII, taken from the paper by T. J. Killian[60] show the variation in $T_e$ and in electron concentration with pressure of mercury vapor. These values were observed at an arc current of 5.0 amp in a tube of diameter 6.2 cm.

59. *Phys. Rev.*, v. 26, 1925, p. 609.

The table gives values of $X$, $N_e$, the *total* number of electrons per centimeter length of column, and $I_p$, the positive ion current density to the walls. It will be observed that $X$ and $T_e$ decrease with increase in pressure. From other observations it has been found that $T_e$ in a mercury vapor discharge exhibits a tendency to decrease somewhat with increase in arc current. The data also indicate that $N_e$ and $I_p$ increase with increase in pressure. Since the tube cross section was 30.2 sq cm, the average values of $n_e$, the concentration per cubic centimeter, varied from $3.7 \times 10^{10}$ to $15.2 \times 10^{10}$. However, as deduced from theoretical concentrations by L. Tonks and I. Langmuir,[61] and confirmed by Killian's measurements, the concentration is a maximum along the axis of the tube and decreases toward the walls, thus establishing a concentration gradient for diffusion.

**Table VIII—Variation in Electron Characteristics With Temperature**

| Pressure in mm | X (volts/cm) | $T_e$ | $N_e$ | $I_p$(ma/cm²) |
|---|---|---|---|---|
| 0.00020 | 0.0932 | 38,000 | $11.1 \times 10^{11}$ | 0.356 |
| 0.00103 | 0.196 | 27,500 | $21.8 \times 10^{11}$ | 0.45 |
| 0.00533 | 0.311 | 19,900 | $45.7 \times 10^{11}$ | 0.505 |

It is important to realize the significance of a value $T_e = 19{,}900$. At this temperature, the *average* kinetic energy of the electrons is

$$\frac{3}{2}\,kT_e = \frac{3}{2}\cdot\frac{19{,}900}{11{,}600}\text{ volts} = 2.56\text{ volts}$$

The fraction of the electrons with an energy in excess of 10.4 volts ($V_i$ for mercury) is

$$\epsilon^{-\frac{10.4}{1.71}} = 0.003$$

Furthermore, as mentioned previously, the walls must become charged negatively with respect to the plasma to such a potential that the electron current flowing in that direction shall be equal to the positive ion current. Applying the equations developed by Tonks and Langmuir, it is found that in this case there is a total drop from the axis to the walls of 11.0 volts, of which about 2.5 occurs in the plasma, leaving a voltage drop in the wall sheath of 8.5 volts. Since the magnitude of this drop increases linearly with $T_e$, it follows that for $T_e = 38{,}000$, the walls would be charged to a negative potential of 16.2 volts with respect to the outer edge of the plasma.

A very complete set of data on the gradient, electron temperature and concentration in a positive column discharge in sodium and sodium plus neon has been published by M. J. Druyvesteyn and N. Warmoltz.[62] Some of this data is shown in Table IX. The measurements were taken with the tube connected to a sodium reservoir maintained at the temperature indicated in the first column. Since

60. *Phys. Rev.*, v. 35, 1930, p. 1238.
61. *Phys. Rev.*, v. 34, 1929, p. 876.
62. *Phil. Mag.*, v. 17, 1934, p. 1.

the tube itself was at 330 deg C, there was no condensation of sodium along the walls of the tube, and while the second column gives the vapor pressure at the corresponding temperature, the actual pressure in the tube varied with distance from cathode owing to migration of sodium ions. The third column gives the pressure of neon as measured by a gauge at room temperature. The values of $X$, $T_e$, and $n_e$ were determined by probe measurements. The last 2 columns give data which will be considered in a subsequent section in connection with energy-balance in a positive column.

It will be observed that, as in the case of measurements with mercury vapor discharges, $T_e$ and $X$ decrease with increases in pressure, while $n_e$ increases. Assuming, according to Schottky's deductions that $X$ varies inversely as tube diameter, $d$, the relative values of $Xd$ and $T_e$ for the same vapor pressure are found to be higher in mercury than in sodium. This is what would be expected in view of the relative values of $V_i$ (and $V_r$). The fact that the voltage gradient is increased by addition of neon when the sodium pressure is low and decreased by addition of neon when the sodium pressure is higher, shows that at the low pressures of sodium the ions are supplied by neon, while at higher pressures of sodium the ions are obtained from the latter. That the sodium, even at 0.0021 mm decreases the gradient in neon at 1.1-mm pressure from what it would be in absence of sodium is evident from a comparison of $Xd$ for pure neon as given in Table VII with values at the same pressure of neon in Table IX.

**Table IX—Data for Positive Column Discharge in Sodium and Sodium Plus Neon. Tube Diameter = 3.6 cm**

| t°C | p(Na) mm | p(Ne) mm | Arc amps | X volts/cm | $T_e$ | $n_e \cdot 10^{-10}$ | $E_R$ Percentage of total | $E_W$ Percentage of total |
|---|---|---|---|---|---|---|---|---|
| 255 | 0.0021 | 0 | 0.2 | 0.432 | 30,950 | 1.01 | 92.2 | 13.3 |
| | | 0 | 1.0 | 0.398 | 19,200 | 4.55 | 93.7 | 13.8 |
| | | 1.1 | 0.2 | 1.021 | 17,600 | 4.45 | 92.5 | 7.1 |
| | | | 1.0 | 0.504 | 9,100 | 39.9 | 88.8 | 12.5 |
| | | 3.0 | 1.0 | 0.461 | 8,050 | 67. | 88.3 | 10.3 |
| 273 | 0.0044 | 0 | 0.2 | 0.748 | 22,750 | 1.25 | 91.4 | 6.0 |
| | | 0 | 1.0 | 0.555 | 12,600 | 8.64 | 91.7 | 8.0 |
| | | 1.1 | 1.0 | 0.481 | 8,050 | 39.9 | 90.5 | 9.9 |
| | | 3.2 | 1.0 | 0.440 | 7,600 | 77.0 | 87.5 | 9.4 |
| 287 | 0.008 | 0 | 1.0 | 0.668 | 9,600 | 14.8 | 92.3 | 6.4 |
| | | 1.07 | 1.0 | 0.517 | 8,050 | 39.8 | 92.0 | 8.6 |
| | | 3.1 | 1.0 | 0.443 | 7,100 | 75.0 | 90.5 | 9.6 |
| | | 5.0 | 1.0 | 0.440 | 6,600 | 97.0 | 87.4 | 8.0 |

It is extremely probable that in a positive column discharge in pure neon the ions are produced by cumulative action, as in the cathodic discharge. The fact that there is a considerably greater number of electrons with energy sufficient to excite atoms to the metastable state than those with energy necessary for ionization by direct impact, must favor the value of $P_e$ as compared with that of $P_i$. There is, however, additional evidence from various sources. The measurements of H. Kopfermann and R. Ladenburg,[63,64] which will be discussed in a subsequent section, show that the concentration of metastable atoms in a positive column discharge is quite high and comparable with the values of $n_e$. In this laboratory, W. F. Westendorp[65,66] has shown that the negative resistance characteristic of a neon positive column and the reactance behavior with a direct current upon which has been superposed a ripple, can be interpreted on the assumption of high concentrations of metastable atoms. In fact, from his measurements of the impedance, Westendorp was able to calculate approximate values of $\tau$, the duration of the metastable state, which are of the same magnitude as those deduced by J. M. Anderson[67] by more exact methods.

63. *Zs. f. Phys.*, v. 48, 1928, p. 26.
64. R. Ladenburg, *Rev. of Modern Physics*, v. 5, 1933, p. 243.

**Table X—Comparison of Voltage Gradient and Electron Temperature Under Similar Conditions for Helium, Neon, and Argon**

| Gas | Arc amp | X volts/cm | $T_e$ |
|---|---|---|---|
| Helium (He) | 0.2 | 2.24 | 49,100 |
| | 0.5 | 2.12 | 53,000 |
| Neon (Ne) | 0.2 | 1.35 | 41,400 |
| | 0.5 | 1.34 | 37,100 |
| Argon (A) | 0.2 | 0.71 | 27,700 |
| | 0.5 | 0.48 | 20,700 |

The data obtained by Druyvesteyn and Warmoltz are in agreement with data obtained in this laboratory by G. R. Fonda and A. H. Young[68] on the characteristics of positive column discharges in neon containing sodium vapor, as influenced by the vapor pressure of the latter. The observations were made on an a-c lamp such as that described in a more recent paper by the same authors[69] and by N. T. Gordon.[70] The diameter of the positive column was 6.3 cm and the arc current 4 amp. With a neon pressure of 1.5 mm the values obtained for $T_e$ as a function of the pressure of sodium vapor, in millimeters of mercury, may be represented by the empirical equation

$$\log T_e = 3.486 - 0.193 \log p$$

which shows that $T_e$ decreases with increase in pressure. It was also observed that $T_e$ decreases with increase in current density. At a sodium vapor pressure of 0.002 mm, $T_e$, according to Fonda and Young, was found to be about 10,000 deg K, which is of the same order of magnitude as the values observed by Druyvesteyn and Warmoltz under similar conditions.

Before proceeding with the discussion of the relation between these observations and the luminous output and efficiency of a discharge in neon plus sodium, it is of interest to mention a set of data obtained by the last mentioned investigators on the values of $X$ and $T_e$, under similar conditions of pressure and current, for the 3 rare gases, helium, neon, and argon. This data is given in Table X. The tube used in the measurements was 4.5 cm in diameter, and the pressure 0.5 mm.

65. *Rev. of Scientific Instruments*, v. 2, 1931, p. 437.
66. C. G. Found, *Phys. Rev.*, 1930.
67. *Can. Jl. Res.*, v. 2, 1930, p. 13; v. 4, 1931, p. 312; v. 7, 1932, p. 434.
68. Opt. Soc. of Am. *Jl.*, v. 24, 1934, p. 31.
69. *G.E. Rev.*, July 1934 v. 37, 1934, p. 331–7.
70. *G.E. Rev.*, July 1934, v. 37, 1934, p. 338–41.

Similar results on discharges in neon have been obtained by R. Seeliger and R. Hirchert.[71] Their measurements also indicate that $T_e$ decreases with increase in current and pressure.

These results show, as has been mentioned already, that under similar conditions, $X$ and $T_e$ decrease with decrease in the ionization (or resonance) potential of the gas. The greater the energy required to form positive ions, the higher the voltage gradient and the higher the electron temperature.

## Light Output in Positive Column Discharge

The electrons in a positive column discharge are distributed throughout the whole volume. Therefore, excitation and ionization must occur in all parts of the discharge, and the light production is thus uniformly distributed throughout the length of the column.

Since the probability of excitation increases with the kinetic energy of the electrons (at least for values of $V$ about 0.5 to 1 volt above the excitation value), it follows that a decrease in $T_e$ must be accompanied by a decrease in the fraction capable of causing excitation. Since $T_e$ decreases with increase in pressure, the probability of excitation at a collision decreases, but the actual probability of a collision is increased because of increased pressure. The consequence of these 2 opposing factors is that the light output of a positive column discharge at constant current density increases with pressure for low values of the latter, attains a maximum value, and then decreases. The maximum in light output as a function of pressure at constant current density is usually quite broad.

Let us now consider the effect of current density at constant pressure. The measurements of Fonda and Young as well as those of Druyvesteyn and Warmoltz show that $T_e$ decreases and $n_e$ increases with increase in arc current. From the data in Table IX it is possible to make an approximate calculation of the relative intensities of $D$-line radiation which might be expected for 2 different current values. Thus for a pressure of 1.1 mm of neon and 0.0021 mm of sodium, the observed values of $T_e$ show that the actual concentrations of electrons with kinetic energy in excess of 2.10 volts, that is

$$n = n_e \epsilon^{-\frac{2.10 \times 11,600}{T_e}}$$

are as follows

at 0.2 amp, $n = 1.145 \times 10^{-10}$
at 1.0 amp, $n = 2.765 \times 10^{-10}$

Thus while the ratio of arc currents is 5:1, the ratio of number of electrons capable of exciting sodium atoms is 2.4:1. Consequently, the total light output should increase 2.4 fold and since the gradient has decreased to $^1/_2$, the luminous efficiency should be practically the same. The last column in Table IX shows that the total energy radiated ($E_R$) which includes both visible and infra-red, was approximately constant. While this does not give any information about the percentage in the visible, it is probably justifiable to assume, in view of other results in the same paper on the distribution of $E_R$ between visible and infra-red, that the fraction in the visible decreases with increase in arc current.

This inference is in agreement with the photometric measurements of Fonda and Young which show that the light output per ampere decreases with increase in arc current. Thus at a pressure of sodium corresponding to 200 deg C (with 1.5 mm neon present) the relative light output per ampere decreased from 74 to 42 for a change in arc current from 1 to 5 amp. At very low current densities, the relative lumen output per ampere increased considerably, so that at 0.075 amp and 265 deg C, an efficiency of 315 lumens per watt was obtained, which represents 66 per cent of $L_0$, the optimum luminous efficiency. A similar result has also been obtained by M. Pirani[72] with sodium vapor discharges in which heat was applied from an external source to evaporate the sodium.

The results obtained by the same investigators on the effect on light output and efficiency of varying the pressure of sodium are in agreement with the conclusion previously stated regarding the existence of a maximum in light output. In this case the maximum values in lumens and lumen per watt are obtained with the sodium at 200 deg C (vapor pressure about 0.0001 mm of mercury).

In the case of a hot cathode positive column neon lamp, it has been found in this laboratory that the light output $L$ varies with current $I$ according to a relation of the form quoted by W. F. Westendorp:[73]

$$L = L_1 I^{2/3}$$

where $L_1$ is a constant. This relation has been found valid over a large range of current.

These observations, that the light output in a positive column discharge increases less rapidly than the current when the pressure is maintained constant, have been interpreted in the previous paragraphs from the point of view of the effect of increased current on the values of $T_e$ and $n_e$. It is also of interest in this connection to discuss briefly some of the results which have been obtained by R. Ladenburg and his associates on the variation with current of the concentration of metastable atoms in a neon positive column discharge. (A review of these investigations has been published by R. Ladenburg.[74] This paper gives references to the previous papers on this topic.)

In such a discharge the relative concentrations of metastable atoms in states $s_5$ and $s_3$ (see Fig. 5) may be determined by measuring the relative intensities of certain lines in the visible region. By combining such measurements with those on the absorption coefficients for the same lines it is possible to determine the actual concentrations of atoms in different excited states.

Results obtained by these methods for a discharge in a tube 0.8 cm diameter containing neon at a pressure of 1 mm are shown in Fig. 10. The curves give the concentrations of atoms in $s_5$ state and different $p$-levels as functions of the current, $I$. The ordinates, $N$, give the concentrations in terms of atoms per cubic centimeter.

For values of $I$ less than 60 ma, the concentration

71. *Ann. d. Physik*, v. 11, 1931, p. 817.
72. *Zeits f. tech. Phys.*, v. 11, 1930, p. 482.
73. *Physics*, v. 3, 1932, p. 193.
74. *Rev. of Modern Physics*, v. 5, 1933, p. 243.

of atoms in $s_5$ state may be represented according to Kopfermann and Ladenburg by a relation of the form

$$N_s = \frac{\alpha I}{\beta I + 1} \tag{37}$$

where $\alpha$ and $\beta$ are constants. This equation is derived on the basis of the following considerations:

The rate of production of atoms in the $s$-level is proportional to the current, so that this can be expressed as $aI$. The rate at which atoms in $s$-levels are destroyed by excitation and absorption of radiation is given by $bN_s \cdot I$. Finally the rate at which atoms in $s$-levels are destroyed by collisions with the wall and other causes is given by $c \cdot N_s$, where $a$, $b$, and $c$ are constant. Hence at equilibrium

$$N_s = \frac{aI}{bI + c} = \frac{\alpha I}{\beta I + 1}$$

where $\alpha = a/c$ and $\beta = b/c$.

At values of $I$ greater than 60 ma, higher powers of the current have to be taken into account, because of cross interactions between atoms already excited by electron impact. Therefore in the steady state the population of a definite level characterized by the index $j$ can be approximately represented by

$$N_j = \frac{\alpha I + \beta I^2}{\gamma I + \delta I^2 + 1} \tag{38}$$

where $\alpha$, $\beta$, $\gamma$, and $\delta$ are constants which are determined empirically from the actually observed curve. This last equation applies to the atoms in any excited level and indicates that $N_j$ passes through a maximum at some value of $I$. Hence the light emitted owing to transitions from these levels must also pass through a maximum with increase in current.

A very important conclusion which is deduced by Ladenburg from curves such as those in Fig. 10 is this: For large currents in the plasma, the ratio of the populations of 2 atomic levels designated by $k$ and $j$ corresponds to a statistical equilibrium at the electron temperature. That is,

$$\frac{N_k}{N_j} = \frac{g_k}{g_j} \epsilon^{-(V_k - V_j)e/kT_e} \tag{39}$$

where $V_k$ and $V_j$ are the excitation potentials of the 2 states, and $g_k$ and $g_j$ are statistical weights, the values of which for different levels in neon are shown in the right-hand column of Fig. 5. For example, from the values of $N$ for the different $p$-levels at about 300 ma, the value of $T_e$ calculated by means of the above equation is 20,200 deg K, whereas from actual observations of $T_e$ such as those given in Table X, a value of about 22,000 deg K is deduced for the particular conditions in Ladenburg's experiments. Thus a determination of $T_e$ enables the calculation at least approximately of the relative concentrations of atoms in the different excited states, and hence it is evident that the light output and luminous efficiency are controlled to a great extent by the electron temperature and the conditions, which, in turn, govern the magnitude of this characteristic.

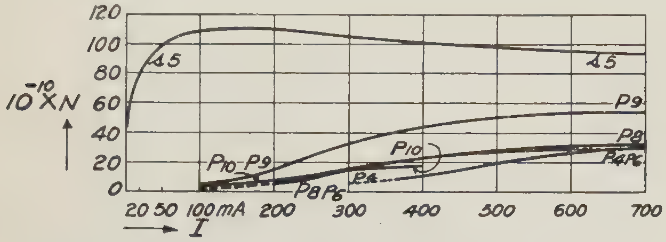



**Fig. 10. Concentrations of neon atoms in different excited states, as functions of current**

## Energy Balance in Positive Column

In their very comprehensive paper on the "Theory of the Arc Plasma,"[75] L. Tonks and I. Langmuir point out that, "The variable quantities involved in the positive column of an arc may be divided into 2 classes, the independent and dependent. Among the former belong the gas used, the tube radius $a$, the pressure $p_0$, and the wall temperature, which, in case the atomic mean free path is comparable with $a$, may be used for the gas temperature $T_g$. One of the arc variables proper must also be included in this category—experimentally it is usually the total arc current $i_A$. The dependent variables are, therefore, the axial electric field $X$, the electron density in the axis $n_0$, the electron temperature $T_e$, the positive ion current density at the wall $I_p$, and the number of ions generated per second per electron $\beta$. These variables are 5 in number and 5 equations will be required for their complete determination."

Of these 5 equations, the most important from the point of view of light production is that designated by Tonks and Langmuir as the energy balance equation which expresses the manner in which the power input $Xi_A$ per unit length is distributed between the various individual processes which take place in the positive column discharge.

From the considerations presented in the previous sections, it follows that the energy is utilized as follows (see also discussion by C. G. Found[76]):

(*a*) *Elastic Collisions, Between Electrons and Gas Atoms.* As has been stated in Part I, the fraction of the energy lost by an electron at each collision of this type is $2m/M$, which has the value $2.72 \times 10^{-4}$, for helium, and is considerably less than this for all other gases. It is therefore evident that the total energy lost in this manner, known as the volume energy must be negligibly small, except at pressures greater than about one centimeter of mercury.

(*b*) *Production of Positive Ions.* At low pressures where recombination between ions and electrons in the plasma itself is extremely improbable, the rate of generation of ions per unit length of discharge column must be equal to the rate at which ions flow to the walls, per unit length of tube, and are neutralized there by an equal current flow of electrons. As has been stated in a previous section, in any discharge the walls become negatively charged with respect to the plasma, and there exists, therefore, a drop, $V_s$, in the wall sheath. The positive ion current flowing to the wall per unit length, which is equal to the electron current per unit length, is given by

$$I_w = I_p \cdot 2\pi a$$

and the energy transmitted to the wall by the ions in virtue of the energy required in passing through the sheath is $I_w \cdot V_s$. While the average energy of the electrons in the plasma is $(3/2)kT_e$, the energy carried to the walls by electrons is $2kT_e$ per electron, so that the total

75. *Phys. Rev.*, v. 34, 1930, p. 876. In order to avoid confusion with symbols used in the present paper, the writer has used different symbols for some of the variables from those used by Tonks and Langmuir.
76. C. G. Found, *G.E. Rev.*, v. 37, 1934, p. 269–77.

energy given up at the surface of tube because of kinetic energy of electrons is $I_w \cdot 2kT_e/e = I_w\ (2T_e/11{,}600)$ watts per unit length. Also the energy evolved by recombination at the walls is $I_w \cdot V_i$. Hence the total energy delivered to the walls (per unit length) because of flow of electrons and ions is

$$E_w = I_w(V_i + V_e + 2T_e/11{,}600) \tag{40}$$

(c) *Production of Excited Atoms.* The energy thus utilized is restored in the form of radiation. Part of this radiation appears as visible light $L$ and if $\overline{V}_\lambda$ designates the average visibility coefficient of the light emitted, the energy converted into light is

$$W_L = \frac{L}{621\,\overline{V}_\lambda} \tag{41}$$

where $W_L$ and $L$ both refer to unit length of tube.

On the other hand, a considerable part of the radiation will be in the infra-red and ultra-violet regions. Some of this energy is transmitted through the walls, while the rest is absorbed and assists in raising the temperature. Let $W_I$ designate the energy transmitted (both ultra-violet and infra-red) and $W_A$, the energy absorbed by the walls. Then the total energy resulting from the production of excited atoms is

$$R = W_L + W_I + W_A$$

On the basis of these considerations we obtain the energy balance equation in the form

$$Xi_A = R + E_w \tag{42}$$

while the light efficiency is given by

$$L_e = \frac{621\ V_\lambda \cdot W_L}{Xi_A} \tag{43}$$

Energy balance measurements have been made by a number of investigators, but in no case, as far as the writer is aware, have data been published in which all the terms in the last 2 equations are given for the same discharge. The first investigation in which the equations developed by Tonks and Langmuir were tested experimentally was that of T. J. Killian.[77] Some of his observations have been discussed in a previous section. He found that as the value of $T_e$ decreased from 38,000 deg K to 19,900 deg K by increasing the pressure of mercury vapor the energy delivered to the walls by recombination, i. e., $E_w$, decreased from 48 per cent to 14 per cent of the total input. Consequently the rest of the energy must have gone into excitation ($R$).

F. L. Mohler has reported results obtained on a positive column discharge in caesium vapor.[78] He found that the first doublet of the principal series at 8,521 and 8,944 deg A (which correspond to the 2 $D$-lines of sodium) contributes most of the radiation. The vapor pressure ranged from 0.001 to 0.3 mm. The tube used had a diameter of 1.8 cm. With currents of 0.2 amp, practically all the power was radiated. With currents of 1 amp or less and pressures less than 0.03 mm the power input was nearly all accounted for in terms of $R$ and $E_w$, with the latter gradually increasing in relative amount until at 4 amp, $E_w$ was about twice $R$. At higher pressures there was an excess of power input which could not be accounted for but was probably due to volume losses and unmeasured for infra-red radiation. "It is reassuring," he states, "to find that over a considerable range the power loss is predominantly radiation of the resonance lines and recombination on the walls. It suggests that an approximate theory can be developed which considers production of ions and of the first excited state exclusively and that other phenomena can be treated independently."

His observations, as Mohler points out, are in agreement with those on the sodium positive column lamp. In the latter, under normal operating conditions the energy radiated in $D$-lines is about 20 per cent of the power input in the positive column, but if external heating is used, a radiation efficiency as high as 70 per cent may be obtained at low current densities as shown by Pirani and by Fonda and Young.

A most comprehensive investigation from this point of view has been carried out by Druyvesteyn and Warmoltz on positive column discharges in mixtures of sodium vapor with neon. In a previous section, some of their observations have been discussed already. In Table IX, the last 2 columns give their results on the percentages of the total power input utilized in radiation $R$ and wall energy $E_w$. It will be observed that the total adds up to over 100 per cent in some cases and less than 100 per cent in others. One conclusion however, is evident—that about 90 per cent of the total energy input was utilized in these experiments in excitation of atoms, and the other 10 per cent in recombination at the walls.

As is seen by an inspection of the energy level diagram for sodium (Fig. 3) the radiation emitted by this vapor consists mainly of the $D$-lines 5,890 and 5,896, and the 3 infra-red lines $\lambda$8,200, $\lambda$11,400, and $\lambda$22,000. The other lines in the visible part of the spectrum emit altogether only about 2 per cent of the total light. Druyvesteyn and Warmoltz do not give data on the manner in which the energy radiated is distributed among the different infra-red lines and the $D$-lines; but in some other cases they found that the infra-red radiation increases from 12 or 14 per cent at the lowest current densities to 50 per cent at the highest current densities. At high current densities the concentration of excited sodium atoms in the $3P$ state is so large that excitation to still higher levels becomes extremely probable.

At higher pressures of neon and especially at higher current densities, Druyvesteyn and Warmoltz observed a residual input energy in excess of $R + E_w$ which they found to be of the same order of magnitude as that calculated for loss by elastic collision; but in pure sodium even at higher current densities and in sodium plus neon at a low pressure of the rare gas, the measurements show that eq 42 gives a fairly satisfactory interpretation of the processes occurring in such discharges.

In this connection it is of interest to calculate the relative concentrations of excited atoms in the $3P$ state in a lamp such as the 10,000-lumen a-c lamp described recently by Fonda and Young. Since the temperature of the bulb is about 220 deg C, the pressure of sodium is about 0.0001 mm, and the concentration of sodium atoms, $n_{Na}$, is $10^{13}$ per cubic centimeter. In a previous section it was mentioned that according to Ladenburg's measurements, the con-

77. *Phys. Rev.*, v. 35, 1930, p. 1238.
78. Bureau of Standards *Jl.*, v. 9, 1932, p. 25.

centrations of atoms in the different states may be calculated by means of the Boltzmann distribution law if the value of the temperature used is that corresponding to $T_e$. According to measurements by G. R. Fonda, the value of $T_e$ in the positive column part of the a-c sodium plus neon lamp is about 8,000 deg K (equivalent to 0.7 volts). Hence the concentration of atoms in the $3P$ state, $n_a$, is given in terms of $n_{Na}$ by the relation

$$\frac{n_a}{n_{Na}} = 3 \cdot \epsilon^{-\frac{2.10}{0.7}} = 0.15$$

and

$$n_a = 1.5 \times 10^{12}/\text{cm}^3$$

This seems to be a reasonable value in view of the measurements on absorption of resonance radiation and on light efficiency.

(While this paper was being proof read, there appeared a paper by O. Gross,[79] which gives probe measurements on a positive column discharge in argon. The results obtained are in general agreement with the formulas obtained by Langmuir and Tonks and also give energy balance measurements which are in agreement with those obtained by other investigators.)

## Concluding Remarks

Ultimately, of course, it should be possible to correlate measurements on the variable in a discharge which Tonks and Langmuir have designated as "dependent," with the concentrations of atoms in different levels, and with the luminous efficiency. In the previous sections, an attempt has been made to give to the reader some idea of the present state of our knowledge in this field. While considerable progress has been made, and there has thus been gained a deeper insight into the fundamental processes which occur in a gas discharge and govern the light production, the actually assured conclusions apply only in the field of low pressure discharges. Thus attempts have been made to extend the probe method to arcs at pressures of a few centimeters of mercury and even to arcs at atmospheric pressure. But no theoretical physicist is certain as yet just how far the conclusions derived by such measurements are valid when applied to such pressures in which new phenomena occur, such as thermal excitation and ionization and recombination of ions and electrons in the plasma itself. Our empirical knowledge in the field of higher pressure discharges is quite extensive and recently there has been a considerable development in the application of a mercury discharge of this nature as a source of light. However, in order to interpret adequately the phenomena in such a discharge it will be necessary to develop new methods by which an understanding can be obtained of the fundamental processes in these cases which compares with that already acquired about low pressure discharges.

In conclusion, the writer wishes to express his indebtedness to C. G. Found for the helpful discussions of the contents of this paper.

79. *Zeit. f. Phys.*, v. 88, 1934, p. 741.

# Transient Voltages in Welding Generators

**In this paper is given a mathematical analysis of the armature terminal voltage of a d-c welding generator at interruption of the short circuit current, with and without neutralizing transformer. Also, consideration is given to the voltage transients across the field circuit winding of the neutralizing transformer caused by the make and break of the armature circuit. Comparisons are shown between oscillograms and calculations for these transient voltages.**

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IN A PREVIOUS paper[1] on this topic the calculation of currents in the armature and field circuits was given consideration and some cases were discussed in which a transformer provided interconnection between the field and armature windings. Since the current of a welding generator is large in magnitude, and at the make and break of the armature circuit has a very high time rate of change, the question of the magnitude of the voltages existing under operating conditions naturally arose, for there is little to guide the engineer in estimating their relative magnitudes. The present paper gives this matter consideration, deriving formulas for the terminal voltage when the short circuit is broken, and for voltages induced in various parts of the armature and field circuits. Machines with and without transformer interconnection between the 2 machine circuits are discussed. Oscillograms and calculated graphs are shown in comparison, verifying the formula developed.

## Assumptions Used in Making Calculations

When applying electrical circuit theory to arc welding machines, certain simplifying assumptions can usually be made. These are as follows:

1. The excitation of the field is from a constant voltage source. While there are exceptions to this, it is almost general. The machines for which the oscillograms are shown and for which the calculations were made had constant excitation from a battery, with a view toward simplifying the calculations.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 14, 1933; released for publication April 27, 1934. *Not published in pamphlet form.*

2. The magnetic circuit of the machine has small eddy current effects, and magnetic saturation does not exist. For present arc welding generators these assumptions are quite legitimate, since the magnetic circuits are usually laminated, and the voltages under operation are but a fraction of the maximum possible voltage.

3. The series and shunt fields are connected differentially, magnetically, to each other.

4. The rotational speed of the machine is constant under all loads.

A diagrammatic sketch of a d-c generator with a transformer connection between armature and field circuits is shown in Fig. 1.

## Assumptions Regarding Currents Under Transient Conditions

The current does not decrease to zero suddenly during the interruption of the armature current, due to the arcing taking place as the electrodes are separated. No rigid equation is possible which would cover all possible cases, but the current may be assumed to decrease exponentially from the initial value to zero, as given by the equation $I\epsilon^{-\alpha t}$. By reference to Fig. 2, the actual current $I\epsilon^{-\alpha t}$ can be obtained mathematically by assuming a current

$$i = -I\,(1-\epsilon^{-\alpha t}) \qquad (1)$$

is applied to the machine during the interruption, if the initial current is $I$. Adding this to $I$ gives $I\epsilon^{-\alpha t}$, the actual current variation. In a large number of instances the current follows approximately a straight line variation from the initial value to zero. In this case the current may be assumed to be made up of the component parts shown in Fig. 3.

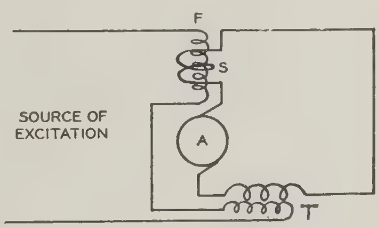
Thus, at $t_0$ the current $-kt$ is applied, followed at $t_1$ (the instant the current becomes zero) by an application of the negative of the first current. Adding these to that previously existing gives the actual current, as is illustrated by Fig. 3.

When the short circuit is broken it is assumed that the terminal voltage is due to the application of currents, shown in Fig. 2 or Fig. 3, to the impedance of the machine viewed from the point at which the interruption takes place. The voltage across an element of the machine is of course the product of these assumed currents and the impedance of that part of the circuit.

Upon the establishment of a short circuit condition the form of current variation can be calculated, as

**Fig. 1. Wiring diagram**

S, series field; F, shunt field; A, armature; T, transformer




was done in the previous paper, since all constants and conditions can be assumed with sufficient accuracy.

In all the analysis which follows the operational method of solution is used with the intention of reducing the formula and procedure to a minimum. No apology need be made for this since many excellent treatises now exist which treat this process.[2]

## Voltage Across Terminals of Generator When Circuit Is Broken

The voltage across the terminals of a d-c generator, when the short circuit is suddenly opened, is

$$e_t = -iZ_1(p) \qquad (2)$$

where $i$ is the current (in operational form) which reduces the final condition to that actually existing,

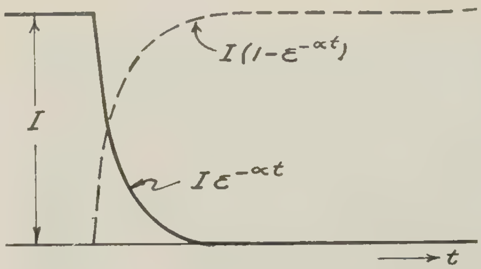



Fig. 2. Decrease of armature current during interruption

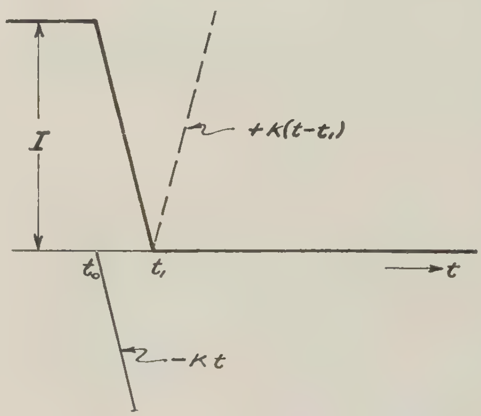



Fig. 3. Components of armature current during interruption. Actual current shown by heavy line

as explained above. $Z_1(p)$ is the impedance of the machine as viewed from the terminals. Thus

$$i = -I\frac{\alpha}{p+\alpha} \qquad (3)$$

if an exponential decay of current is assumed and

$$i = -\frac{k}{p} \qquad (4a)$$

from $t = 0$, to which is added the result of applying

$$i = \frac{k}{p} \qquad (4b)$$

at $t = t_1$ (see Fig. 3).

The impedance of the armature circuit viewed from the terminals is obtained from eq 3, Appendix A, of the previous paper[1] and is

$$Z_1(p) = \frac{(R_1 + K_{11} + L-p)(R_2 + L_2p)-(K_{12} + Mp)(Mp)}{(R_2 + L_2p)} \qquad (5)$$

The terminal voltage under these conditions is, therefore,

$$e_t = \frac{I\alpha[(R_1 + K_{11} + L_1p)(R_2 + L_2p)-(K_{12} + Mp)(Mp)]}{(p + \alpha)(R_2 + L_2p)} \qquad (6)$$

Equation 6 contains $p$ to the same power in numerator and denominator; hence, there is an initial voltage at the moment the current interruption begins.

Assuming that the net mutual inductance between the armature and field circuit is reduced to zero by means of an external transformer coupling between them, this voltage becomes

$$e_t = \frac{I\alpha(R_1 + K_{11} + L_1p)}{(p + \alpha)} \quad (M = 0) \tag{7}$$

The initial value of the voltage is obtained by making $p = \infty$ and neglecting $R_1$ and $K_{11}$ which gives

$$e_t \text{ (initially)} = I\alpha L_1 \tag{8}$$

as would be expected in a circuit which contains resistance and self-inductance only.

Letting $p = 0$, the terminal voltage after the transient condition has passed over, gives for the terminal voltage $I(R_1 + K_{11})$. Since $(R_1 + K_{11})$ is the ratio of open circuit voltage of the generator to the short circuit current, the final voltage is the open circuit voltage prior to short circuit, as it should be. For any condition in general it is

$$e_t = I\alpha \frac{\left[\frac{L_1L_2 - M^2}{L_2} + L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M - \left(\frac{L_1L_2 - M^2}{L_2}\right)(R_2 + \alpha L_2)p + (R_1R_2 + K_{11}R_2) - R_2\left(\frac{L_1L_2 - M^2}{L_2}\right)\right]}{L_2p^2 + (R_2 + \alpha L_2)p + \alpha R_2} \tag{9}$$

The first term of the series gives the initial value of the terminal voltage as an impulse; the second term the voltage variation to normal value, which is dependent only on the form of the applied voltage and the field circuit, as far as time factors are concerned. Thus one exponential term for the second or variable part of the voltage is $A\epsilon^{-\alpha t}$ and the other is $B\epsilon^{-\beta t}$ where $\beta = \dfrac{R_2}{L_2}$.

These results are in conformity with those obtained experimentally. During the period over which the arc is being interrupted the voltage is undergoing erratic and rapid changes, as influenced by the characteristics of the arc and the form of the current to be interrupted, which is dominated by the exponential factor $\alpha$ in the solution. After the arc current has decreased to zero (and the term containing $\alpha$ is at zero value) the exponential term $R_2/L_2$, which is the exponential factor a transient current in the field circuit unaffected by the armature circuit would have, governs the return of the voltage to normal value. That is, after the current in the armature circuit has been interrupted, the terminal voltage returns to normal open circuit voltage at a rate proportional to the unaffected time variation of the field circuit current.

Perhaps a still better assumption as regards urrent variation is that made by eq 4a. This seems to be the more prevalent form, from the results obtained in many oscillograms. Substituting eq 4a in eq 2 gives a voltage from $t = 0$ to $t = t_1$, where $t_1$ is the instant the current is interrupted, as

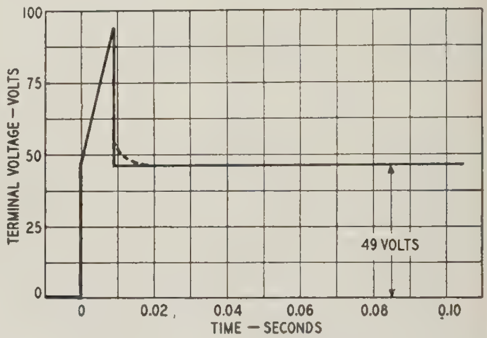
$$e = \frac{k(R_1 + K_{11} + L_1p)(R_2 + L_2p) - (K_{12} + Mp)(Mp)}{p(R_2 + L_2p} \quad 0 < t < t_1 \tag{10}$$

Substituting numerical values which pertain to the oscillogram shown in Fig. 4 the solution is

$$e = 637.5(12.65t + 1.077\epsilon^{-8.6t} - 1) \qquad 0 < t < t_1 \tag{11}$$

At $t_1$, the voltage is that given above plus the voltage due to the application of $e = kt$, which is the negative of the voltage applied at $t = 0$. That is,

$$e = \text{eq (11)} + 637.5[12.65(t - t_1) + 1.075\epsilon^{-8.6(t-t_1)} - 1] \tag{12}$$



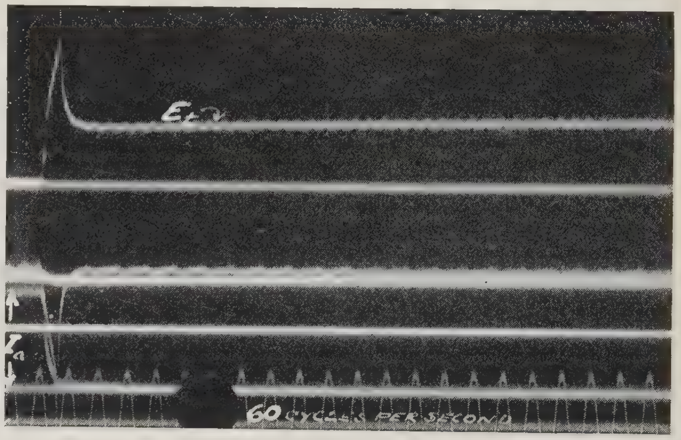
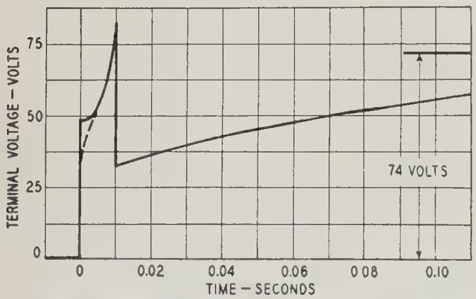




Fig. 5. Oscillogram (below) and calculated graph of armature terminal voltage when short circuit is broken; low mutual inductance

$E_t$, terminal voltage; $I_a$, armature current



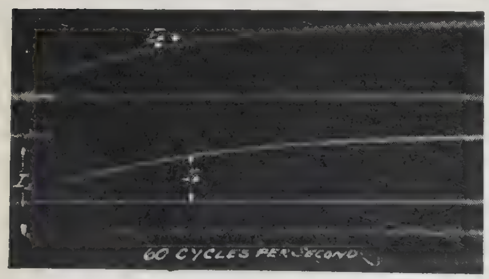




Fig. 4. Oscillogram (below) and calculated graph of armature terminal voltage when short circuit is broken; no transformer

$E_t$, terminal voltage; $I_a$, armature current; $I_f$, field current

for all instances of time after $t = 0$. A plot of eq 12 is shown in Fig. 4, which in general verifies the oscillogram.

In case the mutual impedance between the armature and field circuits is reduced to zero,

$$Z_1(p) = k(R_{11} + K_{11} + L_1 p) \tag{13}$$

and the terminal voltage is

$$e = \frac{k(R_{11} + K_{11} + L_1 p)}{p} \quad 0 < t < t_1 \tag{14}$$

The solution of this equation is

$$e = k[(R_{11} + K_{11})t + L_1] \qquad 0 < t < t_1 \tag{15}$$

to which must be added, after $t = t_1$, the following voltage,

$$e = k[(R_{11} + K_{11})t - t_1 + L_1] \qquad t > t_1 \tag{16}$$

As it was impossible to reduce the mutual impedance to zero with the apparatus available no experimental verification of this was possible, but in Fig. 5 is an oscillogram taken under conditions closely approximating those of negligible mutual impedance; also there is given a mathematical plot of the solution of the terminal voltage for this particular case, which shows good similarity.

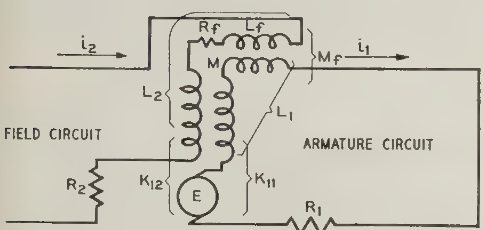



Fig. 6. Equivalent circuit of a d-c generator with separately excited field

The above solutions show that the generator having negligible mutual inductance between armature and field has a tendency toward a greater terminal voltage when the armature circuit is interrupted, but these voltages under the more ideal conditions will not reach excessive values. Arc welding generators are not, except under very unusual conditions, required to operate under such short time intervals of interruption as shown above. In these tests the circuit was broken by large, rather high speed circuit breakers.

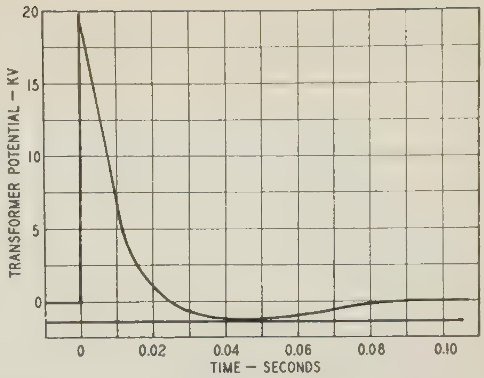
## Voltage Across Transformer Terminals on Short Circuit of Machine

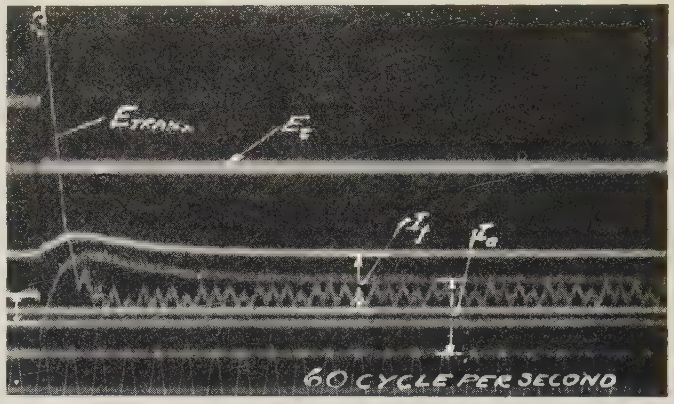
Only the voltage across the transformer winding connected in the field circuit will be given consideration, as the principle involved in the calculation for either winding is the same. The voltage is, for the direction of currents assumed as in Fig. 6, $M_f p i_1 - (R_f + L_f p) i_2$, $M_f$ and $L_f$ being the mutual and self-inductance, respectively, of the transformer winding in the field circuit and $R_f$ its resistance; $i_1$ is the armature current and $i_2$ is the transient component of the field current. The values of $i_1$ and $i_2$ are given in operational form by eqs 3 and 4, Appendix A, of the previous paper.[1]

Thus, for the transformer secondary winding,

$$e = \frac{EM_f p(R_2 + L_2 p) - Mp(R_f + L_f p)}{(R_1 + K_{11} + L_1 p)(R_2 + L_2 p) - (K_{12} + Mp)(Mp)} \tag{17}$$

Fig. 7. Oscillogram (below) and calculated graph of voltage of field circuit winding of transformer when machine is short-circuited




$E_T$, transformer terminal voltage; $I_f$, field current; $E_t$, armature terminal voltage; $I_a$, armature current

In this equation $M$ is the net mutual inductance between the armature and field circuits and $R_2$ is the total field circuit resistance. The numerator is of the same power as the denominator, and there is an initial value of voltage on the application of a short circuit.

The above equation does not contain the voltage due to the resistance drop in the field produced by the normal value of field current for that part of the circuit, for $i_2$ is the transient component of the field current only. Hence, the voltage recorded on the oscillogram is the sum of that given by eq 17 and the resistance drop in the transformer coil due to the current prior to short circuit.

If $M = 0$, the initial voltage is

$$e_{\text{(initial)}} = \frac{EM_f}{L_1} \tag{18}$$

when the short circuit is established, and in general

$$e = \frac{EM_f p}{R_{11} + K_{11} + L_1 p} \tag{19}$$

The solution of this operational equation becomes

$$e = \frac{EM_f}{L_1} \epsilon^{-\gamma t} \tag{20}$$

where

$$\gamma = \frac{R_{11} + K_{11}}{L_1}$$

For the case of a machine in which $M_f = 0.2$ henry and $L_1 = 0.006$ henry (which might be possible values)

$$\epsilon = E \times 33.3\epsilon^{-116.7t} \tag{21}$$

$E$ ranges in value from 70 to 90 volts, hence the initial voltage may be as high as 3,000. To this would be added the voltage drop due to the field current.

An oscillogram of the transformer voltage (in the field circuit) for a particular machine is shown in Fig. 7; also a solution of eq 17, which applies in this case, is shown there, experimentally verifying the mathematical solution. Under the conditions of this test,

$$e = E\,(52.75\,\epsilon^{-83.5t} - 12.23\,\epsilon^{-19.95t})$$

The circuit constants are: $M = 0.2$ henry, $M_f = 0.1$ henry, $R_f = 143.5$ ohms, $R_2 = 545$ ohms, $L_2 = 45$ henrys, $L_1 = 0.006$ henry, and $E = 50$ volts.

When the mutual impedance between the armature and field circuits is reduced to zero, the induced voltage in the transformer winding is counterbalanced by a similar induced voltage in the field winding, which must be taken care of in the design of the machine.

## Voltage Across Transformer Terminals When Short Circuit Is Broken

The voltage at the terminals of the transformer winding in the field circuit (which in magnitude is the same as that at the terminals of the field winding of the generator, except for the resistance drop) is

$$e_s = M_f p i_1 - (R + Lp) i_2 \qquad (22)$$

where $R$ and $L$ are the resistance and inductance, respectively, of the transformer winding inserted in the field circuit. By eq 2 of the previous paper,[1]

$$i_2 = \frac{M_p}{R_2 + L_2 p}\, i_1 \qquad (23)$$

Therefore

$$e_s = \left[M_f p - \frac{(R + Lp)}{(R_2 + L_2 p)}\, Mp\right] i_1 \qquad (24)$$

If $M = 0$,

$$e_s = M_f p i_1 \qquad (25)$$

This value is the lowest possible value that may exist. In this case $i_2 = 0$ and the self inductance and resistance of the field circuit play no part. Thus, if the current in the armature is assumed to be given by eqs 4a and 4b, the transformer voltage for the field circuit is

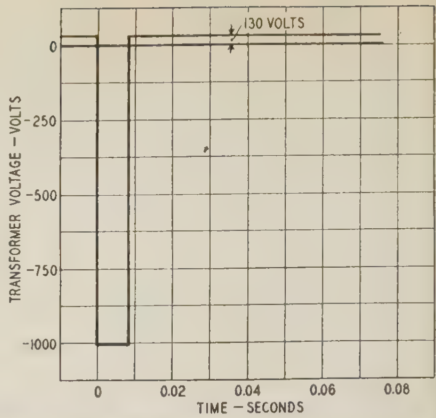
$$e_s = -M_f k \qquad (M = 0) \qquad (26)$$

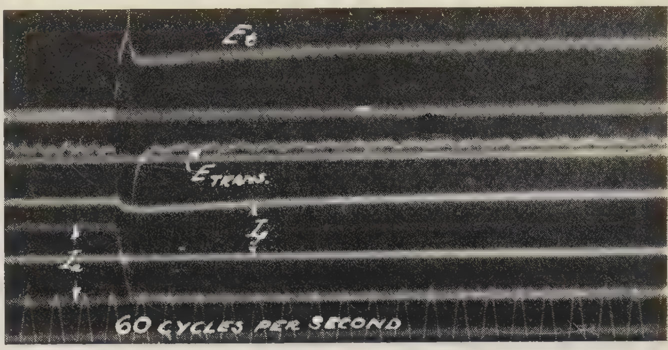
from $t = t_0$ to $t = t_1$. This agrees quite well with the oscillogram shown in Fig. 7 which was taken under the assumed condition.

Should it happen that for a condition other than $M = 0$ the resistance and inductance of the transformer field winding and the machine field winding are similar, by eq 24, the same voltage-time relationship would hold, except for relative magnitude. Since this is approximately so, the voltage across the transformer winding assumes a more or less constant value during the transient state for all conditions under which the oscillograms were taken.

**Fig. 8. Oscillogram (below) and calculated graph of voltage of field circuit winding of transformer when short-circuit current is broken**

$E_T$, transformer terminal voltage; $I_f$, field current; $E_t$, armature terminal voltage; $I_a$, armature current




## Conclusions

The terminal voltages upon the interruption of the armature current in arc welding generators are not excessive under operating conditions, but are likely to be higher in machines which use transformer coupling between armature and field winding for the purpose of eliminating overshooting of the current upon sudden changes in circuit conditions. The transient value of this voltage is not likely to exceed more than twice the normal open-circuit terminal voltage of the machine. The latter type of machine has an instantaneous recovery of normal open-circuit voltage upon the interruption of the armature current, as may be seen in Fig. 8, which is an advantage from the welder's point of view.

Although in the older types of d-c generators, built without neutralizing transformers, the terminal voltage of the field was of normal value under transient conditions, the neutralized arc welding generator may have terminal voltages of a few thousand across the transformer winding in the field circuit, and likewise across the field winding coils of the generator itself. If care is used in designing the machine the voltage is not of such a value that the proper insulation cannot be provided.

## List of Symbols

$R_1$ = resistance of armature circuit
$R_2$ = resistance of field circuit
$L_1$ = self-inductance of armature circuit, including the armature winding, series field, and any reactor or other device which may be in that circuit
$L_2$ = total self-inductance of the field circuit
$M$ = mutual inductance between the armature and field circuit. Saturation is assumed negligible
$K_{12}$ = rotation voltage constant between shunt field current and

voltage induced by the rotation of the armature in the magnetic field produced by the field current

$K_{11}$ = rotational voltage constant for the series field current

$E$ = open circuit (or induced voltage) produced by the field current prior to a transient condition in the armature

$p$ = d/d$t$

$t$ = time in seconds

$L_f$ = self inductance of transformer winding in the field circuit

$M_f$ = mutual inductance of transformer winding in the field circuit

$R_f$ = resistance of transformer field circuit winding

$\alpha$ = exponential factor for arc current

$\beta$ = $R_2/L_2$

$\epsilon$ = base of natural logarithms

$k$ = rate of change of armature current

$\gamma = \dfrac{R_{11} + K_{11}}{L_1}$

$i_1$ = armature current

$i_2$ = field current (transient component)

$e_t$ = transformer terminal voltage (winding in field circuit)

## References


1. Transients in Arc Welding Generators, A. R. Miller. A.I.E.E. Trans., v. 52, 1933, 260–67.
2. Heaviside's Operational Calculus, Berg. McGraw-Hill Book Company.


# Overvoltages on Transmission Lines


**Observations of line-to-ground voltages have been made under routine operating conditions on an isolated neutral system, a Petersen coil system, 3 neutral resistance grounded systems, and 2 directly grounded systems. Results of these observations are given in this paper. Measurements were made with oscillographs supplemented, on all but 2 systems, by surge recorders.**



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IT HAS long been recognized that, under certain conditions involving faults to ground, dynamic voltages larger than the normal line-to-line voltage may exist on the unfaulted phases of a system operated with neutral isolated or grounded through substantial values of impedance. Dynamic overvoltage is dependent among other things upon the impedance through which the neutral is grounded. The term dynamic overvoltage, as used herein, includes transient voltages due to an arc at the fault, but does not include high frequency surge voltages due to lightning or switching. Both theoretical and experimental investigations indicate that the magnitude of lightning and switching surges is not dependent upon the method of grounding the system neutral and these types of surges are not considered in this paper. Although conditions other than the type of system grounding may affect the dynamic overvoltage under fault conditions, they are not likely to cause an effect as large as that mentioned above.

A knowledge of the probable magnitudes of dynamic overvoltages is of importance not only in relation to the general insulation level of a system but also in connection with the selection of protective gaps and lightning arresters. Several theoretical methods of estimating the maximum value of dynamic overvoltage on systems isolated or grounded through substantial values of neutral impedance have been published. These are based upon certain assumptions regarding the characteristics of arcs to ground and lead to various estimates of maximum voltage, ranging from 3.5 to 19 times normal.[1–5] Voltages up to 3.5 times normal, as measured in staged tests, have been reported in 2 recent Institute papers.[6,10] There is, however, little published material relating to the measurement of these voltages during operating conditions. This paper gives the results of an experimental study of this matter by one of the project committees of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, in coöperation with 4 power companies. The paper does not provide data regarding overvoltages which may be experienced on cable systems, as the observations were conducted on overhead transmission lines except for one system, in which approximately 20 per cent of the system mileage was cable.

## Method of Measuring Overvoltage

In these investigations overvoltages on operating systems have been measured by automatic oscillographs connected through wye-wye connected potential transformers to record the line-to-ground voltages, supplemented in several cases by surge-voltage recorders.

The oscillographs utilized in this investigation are an improved form of the continuous film oscillograph described in an Institute paper in 1929.[7] Features making them particularly well suited for this type of investigation are as follows:

1. The speed of operation is such that, after the tripping value is reached, only about the first cycle of a disturbance is unrecorded.
2. The frequency response characteristic of the string type gal-


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1. For all numbered references see list at end of paper.

vanometers (utilized in all but 2 of the instruments) is practically uniform up to about 3,000 cycles. This is especially advantageous in recording transient disturbances within this frequency range or voltages of irregular wave-shape.

3. The date and time of each oscillogram are recorded by photographing on the film at the end of the oscillogram, a calendar clock, thus providing a means for correlating a particular oscillogram with records from other instruments on the system and with operating records.

To supplement the records from the magnetic oscillograph and provide information on the existence of high frequency surges associated with dynamic overvoltage, or voltage disturbances that might occur before the oscillograph could come into operation, surge voltage recorders were installed on 4 of the systems under study. The instruments were coupled to the line through capacitance potential dividers, and so connected as to minimize the effect of leakage across the insulators.

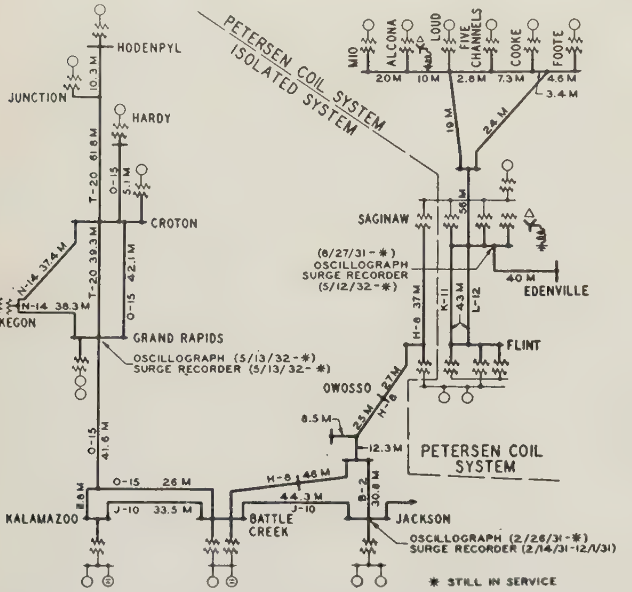


**Fig. 1. 140-kv isolated neutral and Petersen coil systems of the Consumers Power Company**

Surge voltage recorders utilize Lichtenberg figures[8] as a means of determining the type and magnitude of a surge voltage. The instruments used in this investigation are similar to those which have been extensively used in lightning investigations on power lines, except for certain modifications, such as the use of moving picture film which is automatically stepped forward after each record, and means for photographing a clock thus giving the time and date of each record.

## Extent of Available Data

The extent of the data included in this paper and relevant information regarding the systems from which they were obtained are given in Table I. It will be seen from this table that observations were made on 6 systems having a combined mileage of over 2,500 circuit miles, and operating with neutral isolated, grounded through resistance or Petersen coils, or solidly grounded. The records cover periods of observation ranging from 9 months to $2^1/_2$ years.

A sketch of the 60-cycle 140-kv lines of the Consumers Power Company is given in Fig. 1. The Petersen coil system is metallically isolated from the rest of the system, which is operated with neutral isolated. This figure also shows the lengths of the various circuits, the points at which oscillograph and surge recorder observations were made and the period of observation at each point.

The south and west zone 33-kv systems of the Public Service Company of Northern Illinois are shown on Fig. 2, together with the locations of recording instruments and the points of neutral grounding. During part of the period of observation the west zone system was grounded at 2 points through 50-ohm resistors, and solidly grounded at 2 fairly remote points. The relaying was such that for many of the faults the solidly grounded section

**Table I—Data Relating to Systems Under Observation**

| System | Voltage Kv | Type of Neutral Grounding | Length of System Circuit Miles | Period of Observation** Months | Period of Observation** Lightning Seasons | No. of Records Included in Analysis |
|---|---|---|---|---|---|---|
| Consumers Power Co. | 140 | Isolated | 573–800 | 29 | 2.8 | 350 oscillograms |
| | | | | 25 | 2.4 | 157 surge records |
| Consumers Power Co. | 140 | Petersen Coil | 226–274 | 25 | 2.1 | 166 oscillograms |
| | | | | 20 | 1.9 | 38 surge records |
| Public Service Elec. and Gas Co. | 26 | 75 ohms resistance at 1 point | 126 open wire, 32 cable | 29 | 2.3 | 101 oscillograms<br>No surge recorder installed |
| Public Service Co. of Northern Illinois, South Zone system | 33 | 50 ohms resistance at 3 points | 570 open wire | 29 | 2.5 | 290 oscillograms |
| | | | | 29 | 2.5 | 20 surge records |
| Public Service Co. of Northern Illinois, West Zone system | 33 | 50 ohms at 2 points, solidly grounded at 2 other points | 240 open wire | 5.5 | 0 | No oscillograph records above 1.2 times normal |
| | | | | 13 | 1.4 | 44 surge records |
| Public Service Co. of Northern Illinois, West Zone system | 33 | Solidly grounded at 4 points | 240 open wire | 10 | 1 | No oscillograph records above 1.2 times normal |
| | | | | 10 | 1 | 10 surge records |
| Illinois interconnected system* | 33 | Solidly grounded at 2 points | 800 open wire | 9 | 1 | 75 oscillograms<br>No surge recorder installed |

Central Illinois Light Co., Central Illinois Public Service Co., and Superpower Co. of Illinois.
Where 2 periods are listed the first applies to oscillograph and the second to surge recorder observations.

was separated from that part of the system to which the recording instruments were connected. However, there has been no indication from oscillograms of an increase of voltage on this system when the solidly grounded section has been disconnected. About the first of February 1933, the resistance grounds were replaced by solid grounds and since that time this system has been operated with solid grounds at all 4 points.

Oscillographic observations only were made on the other 2 systems. On the 33-kv solidly grounded interconnected system in the vicinity of Springfield, Illinois (the power companies concerned are the Central Illinois Light Company, Central Illinois Public Service Company, and the Superpower Company of Illinois), oscillographs were installed at Powerton generating station, the main neutral grounding point, and at East Springfield, a non-grounded station, the 2 stations being at opposite ends of a 64-mile line. The records of voltage to ground procured from these instruments are incidental to the principal purpose for which the instruments were installed.

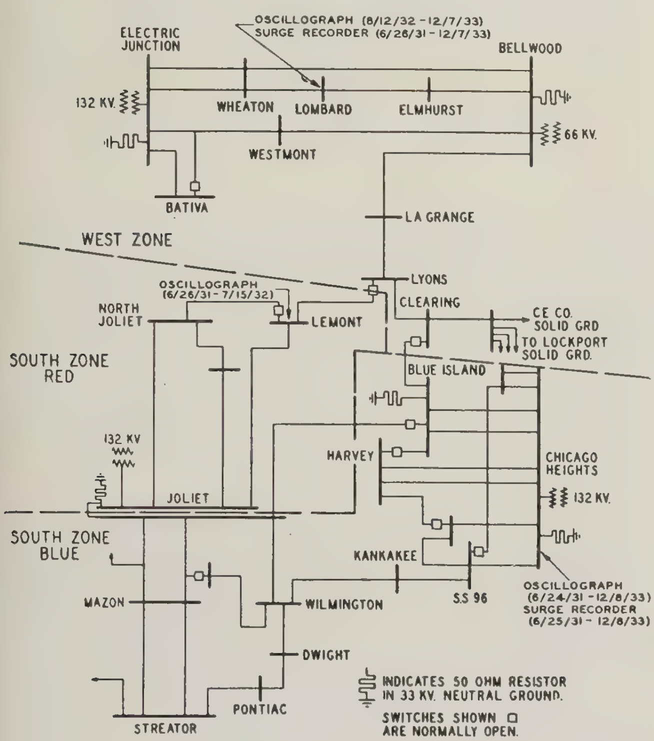


**Fig. 2. 33-kv system of the Public Service Company of Northern Illinois**

The 26-kv system of the Public Service Electric and Gas Company is a radial system, grounded through resistance at the substation at which power is supplied to the system. The oscillograph is located at this point.

## Method of Analysis

In the analysis of the oscillographic data all records showing evidence of a disturbance have been included whether or not they were correlated with operating records. Records correlated with or of a type attributable to switching have been omitted, and on one system records of voltage less than 15 per cent above normal have been arbitrarily omitted since it was frequently difficult to determine whether they were due to an actual disturbance or to a slight abnormality in the voltage.

Surge records include those due to lightning and switching surges as well as dynamic overvoltages. Other investigations have indicated that the characteristics of the figures are an indication of the duration and nature of the overvoltage. It has been found that lightning surges produce only positive or negative figures, or figures of a type sometimes classified as highly-damped oscillatory.[9] Switching surges also usually produce highly-damped figures. On the basis of these observations all unidirectional or highly-damped figures have been attributed to lightning or switching and therefore have been omitted from the analysis given in this paper. Medium and slightly damped figures are usually associated only with dynamic voltages either at fundamental frequency or at some higher harmonic frequency, since under fault conditions these voltages may persist and thus produce dense Lichtenberg figures, indicating many reversals or alternations in voltage. There remains a large group of mixed figures having the characteristics of a medium damped figure with a superposed figure of a type associated with lightning or switching. It is often difficult to determine the exact line of demarcation between the 2 types of figures, and to avoid the possibility of eliminating some voltages which may be caused by a fault-to-ground, 2 cumulative percentage curves have been prepared, one from the maximum recorded voltage of all medium damped and mixed figures, the other from the maximum voltage of the medium damped figures and the estimated medium damped portion of the mixed figures.

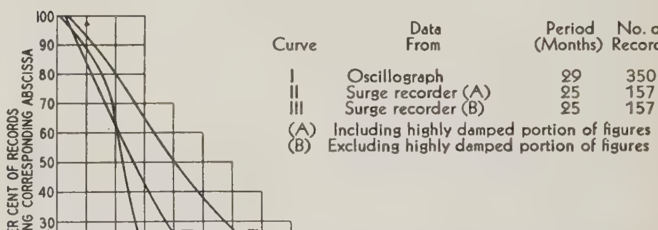


**Fig. 3. Magnitude distribution of overvoltages on 140-kv isolated neutral system**

In order to simplify and facilitate the measurement of the records from the surge recorders, only those showing voltages 15 per cent or more above normal were utilized.

Typical Lichtenberg figures secured in these investigations are shown in the accompanying illustrations. In some instances when voltage persisted for an appreciable time, records of the type illustrated in Figs. 6*A* and 9*C* were obtained. They

are due to the persistence of the voltage until after the film starts to advance. The film begins to move from 1 to 2 sec after the recorder is tripped and moves forward at the rate of about one inch per second. The extended portion of a record has been considered as well as the main figure and the maximum value indicated by either is the value used for the given disturbance.

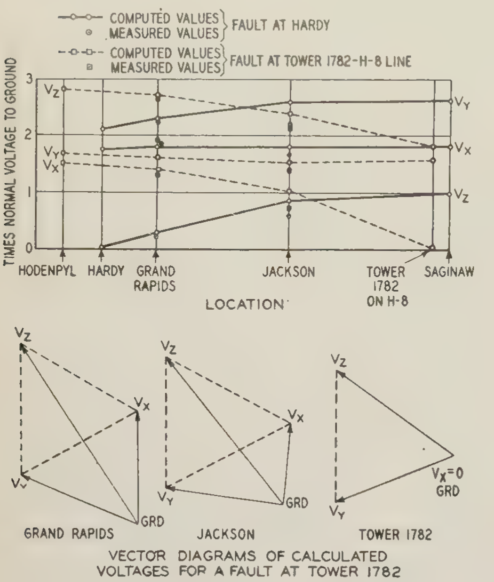


**Fig. 4. Comparison of measured and computed line-to-ground voltages on 140-kv isolated neutral system**

In cases of one-phase-to-ground faults the magnitudes of the overvoltages on the 2 sound phases were usually different. In preparing the curves, the maximum voltage shown by an oscillogram or surge record was used irrespective of the phase on which it occurred. Where records were obtained at more than one location for a given fault, the maximum voltage recorded, irrespective of instrument location, was used.

In analyzing the oscillograms and surge records the maximum peak or crest value, respectively, of the voltage to ground has been measured. This value is divided by the nominal peak voltage to ground of the system to secure the "times normal voltage to ground" used in presenting the results.

These values, as determined from oscillograms and surge records, respectively, are shown in the form of cumulative percentage curves of the type illustrated in Fig. 3. On these curves the abscissas indicate overvoltage expressed as a multiple of the normal system voltage to ground. The ordinates show the percentage of the total number of records considered which exceed the corresponding abscissas.

## Results of Observations—Isolated Neutral System

The highest overvoltages, as would be expected, were observed on the isolated neutral system. By reference to Fig. 3 it is seen that, according to oscillographic measurements, 80 per cent of the disturbances produced voltages to ground equal to or exceeding the line-to-line voltage (1.73 times normal). The maximum value recorded was 3.9 times normal. Fundamental frequency calculations indicate that on an extensive system of this type, involving large charging currents during faults, overvoltages above 1.73 times normal may be expected. This is indicated by Fig. 4, the upper portion of which shows a comparison between measured and computed line-to-ground voltages, for 2 faults of known location. The vector diagrams in the lower portion of this drawing apply for a fault at pole 1782 and show the computed voltages at the locations indicated just above the respective diagrams. They illustrate how far the neutral (ground) point shifts outside the triangle of delta voltage and that the delta voltage remains normal even though the voltages to ground are badly unbalanced. Oscillograph observations also show that normal line-to-line voltage is maintained during one-line-to-ground faults.

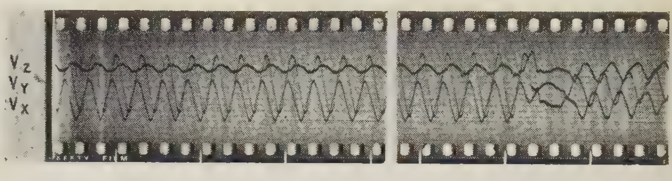

**Fig. 5. Typical oscillogram of one-line-to-ground fault on 140-kv isolated neutral system**

$V_x$, $V_y$, $V_z$ = line-to-ground voltage

The 5 highest overvoltages recorded by the oscillographs were all due to disturbances on the same line, namely, the *H*-8 line which forms part of the eastern side of the system. The highest value was recorded during a fault caused by the boom of a dredge fouling the line. The next 4 highest resulted from insulator arc-over due to lightning.

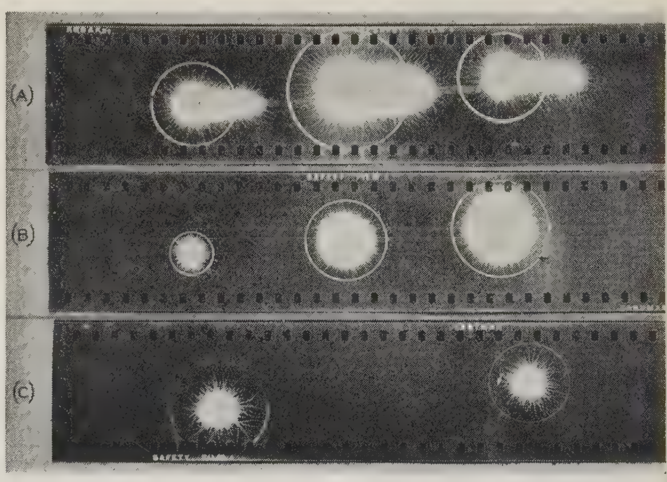


**Fig. 6. Lichtenberg figures from 140-kv isolated neutral system**

A. Medium damped figure, film in motion before fault cleared
B. Medium damped figure
C. Combination highly damped, medium damped figure

## Table II—Comparison of Voltages From Oscillographs and Surge Recorders; One-Phase-to-Ground Faults; Isolated Neutral System

| Case No. | Maximum Voltage to Ground (Times Normal) Measured by | | | | Correlation With Troubles on the Power System |
|---|---|---|---|---|---|
| | Oscill. | Surge Recorder | | | |
| | | Type of Fig. | Over-all Value | Estimated Medium Damped Portion | |
| 1 | 2.9 | HM | 5.0 | 2.8 | Lightning**; *H*-8 between Saginaw River and Flint |
| 2 | 2.7 | HM | 4.8 | 2.8 | Arc between *X*-*Y* conductors and to ground wire. Cause unknown, possibly kite |
| 3 | 2.0 | HM* | 4.1 | 3.2 | Lightning; line *O*-15 tripped at Kalamazoo |
| 4 | 2.5 | HM* | 4.1 | 2.8 | Lightning; line *H*-8 at tower No. 2,500 between Delhi and Owosso |
| 5 | 2.2 | HM* | 4.3 | 3.0 | Lightning; line *H*-8 at tower No. 2,585 between Delhi and Owosso |
| 6 | 2.4 | M* | 4.5 | 4.5 | Lightning; line *H*-8 at tower No. 2,580 north of Delhi |
| 7 | 2.4 | HM* | 5.4 | 4.3 | Lightning; line *H*-8 at tower No. 2,573 between Delhi and Charlotte |
| 8 | 2.4 | HM* | 5.4 | 3.9 | Lightning; line *J*-10 at tower No. 6,083 between Battle Creek and Blackstone |
| 9 | 2.5 | HM* | 5.6 | 4.3 | Lightning; line *J*-10 between Battle Creek and Blackstone and line *H*-8 at Charlotte |
| 10 | 2.4 | M | 4.1 | 4.1 | Lightning; line *H*-8 north of Garfield Ave. |
| 11 | 2.2 | HM | 3.4 | 1.3 | Lightning; location unknown |
| 12 | 2.5 | HM | 4.3 | 2.8 | Lightning; line *N*-14 between Croton and Muskegon |
| 13 | 2.3 | HM | 4.5 | 2.5 | Lightning; line *T*-20 between Croton and Hodenpyl |
| 14 | 2.3 | HM | 2.6 | 1.3 | Lightning; location unknown |
| 15 | 2.2 | HM* | 3.3 | 2.1 | Lightning; line *O*-15; location unknown |

* Film in motion before fault cleared.
** In all cases reported above as due to lightning, insulator flashover only was involved.
Duration of overvoltage at approximately value shown in column 2 exceeded 20 cycles in all cases.
M = Medium damped figure.
HM = Combination highly damped and medium damped figure.

Sections of an oscillogram typical of the type obtained during a fault on this system are shown in Fig. 5. The left-hand section shows the beginning of the disturbance and the right-hand section the end of the disturbance, including a few cycles of normal voltage. The peculiar flattening of the voltage waves observed on many of the oscillograms at the end of the disturbance has been associated with circuit breaker operation but has not been completely explained.

A considerable number of oscillograms were correlated with switching. These records, which were excluded in preparing the overvoltage curves, were of 1 to 3 cycles duration. They showed voltages ranging up to a maximum of 1.9 times normal but more than 60 per cent of them were below 1.2 times normal.

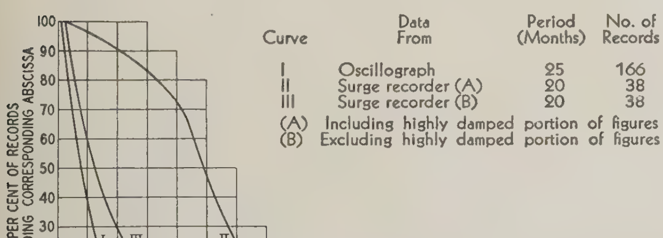


Fig. 7. Magnitude distribution of overvoltages on Petersen coil system

Curves II and III of Fig. 3 are the cumulative percentage curves of the overvoltages recorded by the surge recorders, the former including and the latter excluding the portion of the figures having the characteristics of unidirectional or highly damped surges. These curves are not directly comparable to Curve I partly because the periods of observation with the 2 types of instruments were not the same and partly because faults producing oscillograms sometimes produced no surge records and *vice versa*. The maximum medium damped type of Lichtenberg figure obtained, illustrated in Fig. 6*A*, indicated an overvoltage of 5.4 times normal. It was not possible to correlate this record with any specific power system disturbance, as the clock recording the time of operation was out of order at the time. Other records from this system are shown in Figs. 6*B* and 6*C*.

In general, it was found that, where simultaneous oscillograms and surge records were obtained of the same fault, the latter indicated dynamic overvoltages somewhat larger than those shown by the oscillographs. In order to show the relative comparison between the overvoltages indicated by the 2 types of instruments, 15 cases for which correlation between the 2 have been established are given in Table II together with the maximum line-to-

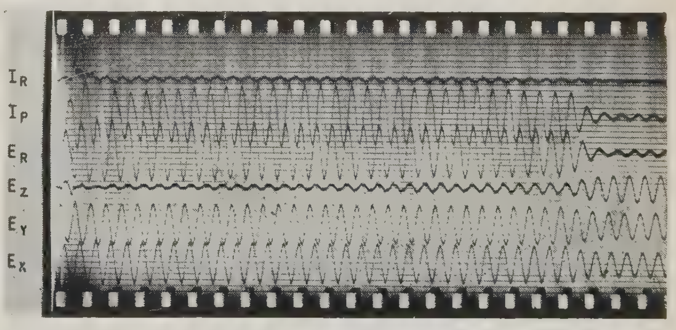


Fig. 8. Typical oscillogram of one-line-to-ground fault on Petersen coil system

$I_R$ = residual current in Saginaw-Emery Junction line
$I_P$ = Petersen coil current
$E_R$ = residual voltage to ground
$E_X$, $E_Y$, $E_Z$ = line-to-ground voltage

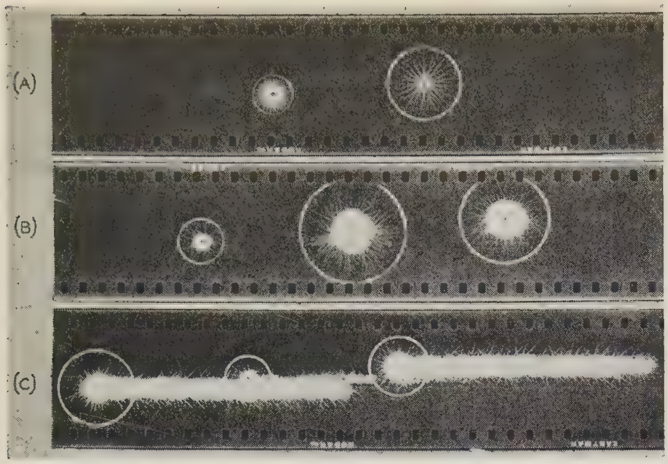


**Fig. 9. Lichtenberg figures from Petersen coil system**

A. Highly damped figure
B. Combination highly damped, medium damped figure
C. Combination highly damped, medium damped figure. Film in motion before fault cleared

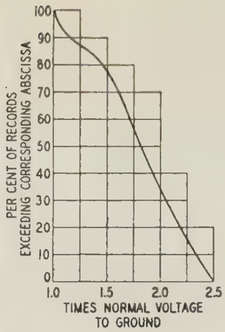


**Fig. 10. Magnitude distribution of overvoltages on 26-kv neutral resistance grounded system. Data from oscillograms**

Period of observation 2 years, 5 months (7/29/31 to 1/1/34). Total records—101

ground voltages indicated by each instrument and the type of the Lichtenberg figure recorded.

## Petersen Coil System

In Fig. 7 are shown the results of the observations on the Petersen coil system, curve I applying to the oscillograph and curves II and III to the surge recorder measurements. In Fig. 8 is an illustration of a typical oscillogram and Figs. 9*A*, 9*B*, and 9*C* are types of Lichtenberg figures from this system. Table III shows, for a number of faults for which records on both instruments were obtained, the comparison between the oscillograph and surge recorder measurements. It will be noted that in all cases listed in the table the trouble was attributed to lightning, and as the faults were self-clearing a definite fault location was determined in only one case. In 3 of the cases highly damped types of figures only were obtained and in some others the medium damped portion of the figure indicates voltages less than those shown by the corresponding oscillograms. In general these were cases in which the trouble cleared within 3 or 4 cycles and in which the voltage of each succeeding half cycle decreased in amplitude. On sustained faults the tendency of the surge recorder to show somewhat higher dynamic overvoltages than the oscillograph is in accord with the results of tests made in connection with the installation of the Petersen coil.[10]

## Systems Grounded Through Neutral Resistance

*Public Service Electric and Gas Company.* This system, as previously stated, is grounded at one point only through a 75-ohm neutral resistor. One oscillograph element measured neutral current and gave a positive indication of those faults which involved ground current. Only records due to accidental disturbances and showing neutral current were utilized in this study. The cumulative percentage curve of overvoltages for this system is shown in Fig. 10. A section of an oscillogram typical of the majority of records from this system is shown in Fig. 11*A*. This oscillogram, obtained during an oil circuit breaker bushing failure, also illustrates the development from a 1-phase-to-ground to a 2-phase-to-ground fault at, according to the trouble record, the same point. In Fig. 11*B* is illustrated an intermittent spit-over followed finally by a complete breakdown; this is an example of the apparent extinction and reëstablishment of fault current. The fault was caused by a cable splice failure.

During the course of the observations 3 different series of tests were made by the power company in which a one-line-to-ground fault was produced by closing in a circuit breaker on a grounded conductor. Twenty records were obtained, the voltage to ground ranging from 1.83 to 1.93 times normal. Wave shape was uniform and undistorted.

*Public Service of Northern Illinois—33-Kv South Zone Network.* Throughout the period of these observations this network was split into 2 parts known as the South Zone Red and South Zone Blue networks, by sectionalizing the bus at the Joliet substation. However, the neutrals of the 2 networks were grounded through the same resistor at Joliet and consequently overvoltages resulting from faults on either network appeared in the other due to the voltage rise across the common resistor. For this reason the oscillographic data on overvoltages as obtained from the 2 networks have been combined for the purposes of this paper. Curve I of Fig. 12 shows the cumulative percentage curve of overvoltage prepared from oscillograms from these networks. The maximum value of overvoltage recorded was approximately 2 times normal. The record was correlated with circuit breaker operation but the cause and nature of the fault was unknown.

Surge records were obtained at only one point on the South Zone network, namely, at Chicago Heights. The results are shown by Curves II and III of Fig. 12. The largest figure attributed to dynamic voltage showed a value of 2.6 times normal and resulted from a bushing failure at a substation not far from the location of the surge recorder.

*Public Service of Northern Illinois—33-Kv West Zone Network—Two Neutral Resistor Grounds.* The results given in this section apply only to the period during which the network was grounded through 50-ohm neutral resistances at Electric Junction and Bellwood and directly grounded at 2 other

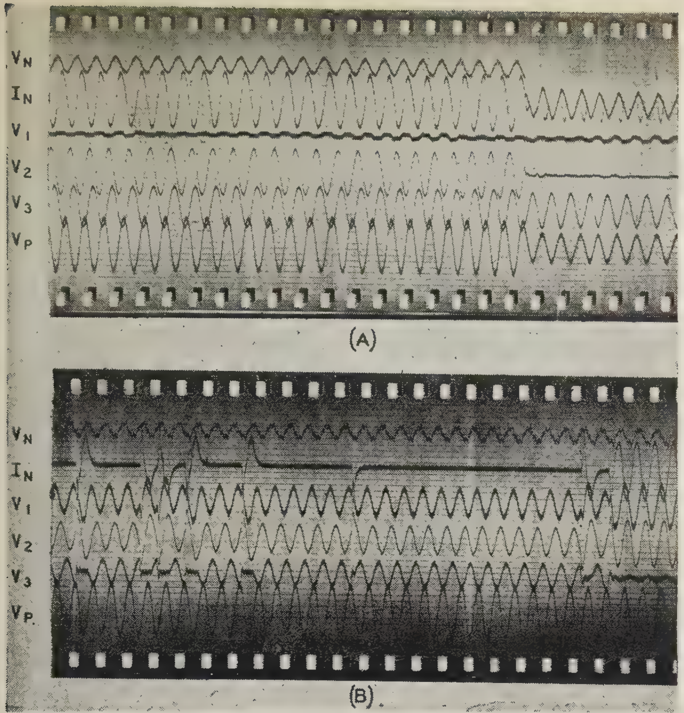


**Fig. 11. Oscillograms of line-to-ground faults on 26-kv neutral resistance grounded system**

A. Typical record
B. Intermittent spit-over followed by complete breakdown
$V_P$, $V_N$ = positive and negative sequence voltage
$V_1$, $V_2$, $V_3$ = line-to-ground voltage
$I_N$ = neutral current

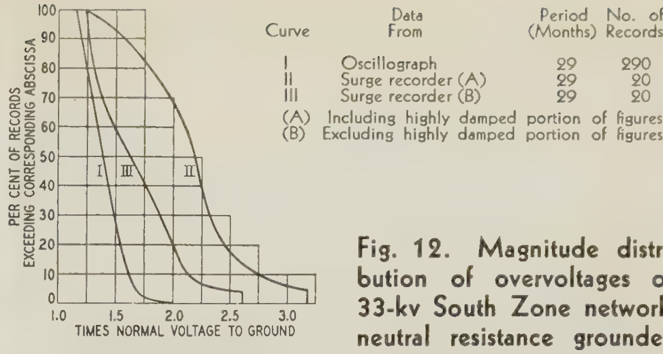


**Fig. 12. Magnitude distribution of overvoltages on 33-kv South Zone network, neutral resistance grounded**

points fairly remote from the main portion of the network. During one-line-to-ground faults on that portion of the network centering around the resistor grounded neutrals, the total fault current divided about equally among the 4 neutrals. During the 5.5-month period that oscillograph records were obtained no voltages to ground greater than 1.2 times normal were recorded. A cumulative percentage curve was not plotted due to the few records of overvoltage obtained.

The majority of the records obtained with the surge recorder showed either a highly damped figure alone or a highly damped figure with a (less than 31-kv crest) very dense center; next in frequency of occurrence were the highly and medium damped figures mixed. A few records showing only medium damped figures were secured. In Fig. 13*A* and 13*B* are sample records from this system. The results of the surge recorder observations are shown by Fig. 14, Curve I being prepared from the voltages shown by the over-all figures and Curve II from the portion of the figures attributed to dynamic overvoltage. Only figures whose medium damped portions exceeded 31-kv crest were used.

## Directly Grounded Systems

*East Springfield and Powerton Observations.* While the oscillographs at Powerton and East Springfield were not installed primarily for the overvoltage study, they provided an opportunity of obtaining data on this subject from a system having solidly grounded neutrals. At Powerton, 1 of the 2 points

**Table III—Comparison of Voltages From Oscillographs and Surge Recorders; One-Phase-to-Ground Faults; Petersen Coil System**

| Case No. | Maximum Voltage to Ground (Times Normal) Measured By: Oscillograph — Voltage | Oscillograph — Duration* Cycles | Surge Recorder — Type of Fig. | Surge Recorder — Over-all Value | Surge Recorder — Estimated Medium Damped Portion | Cycles Duration of Disturbance, From Oscillogram | Correlation With Power System Troubles |
|---|---|---|---|---|---|---|---|
| 1 | 1.6 | 49 | M | 2.5 | 2.5 | 49 | Lightning; Saginaw River 177 operating open |
| 2 | 1.3 | 1 | H | 3.2 | | 2 | Lightning; location unknown |
| 3 | 2.0 | 2 | H | 2.1 | | 4 | Lightning; location unknown |
| 4 | 1.7 | 68 | HM | 4.1 | 1.7 | 68 | Lightning; location unknown |
| 5 | 1.8 | 10 | H | 2.1 | | 11 | Lightning; location unknown |
| 6 | 1.8 | 33 | HM | 4.1 | 1.9 | 48 | Lightning; location unknown |
| 7 | 1.8 | 170+ | HM | 3.9 | 2.1 | 170+ | Lightning; fault on tower No. 1618, *X* phase |
| 8 | 1.6 | 1 | HM | 3.2 | 1.3 | 3 | Lightning; location unknown |
| 9 | 1.5 | 1.5 | HM | 3.6 | 1.3 | 3 | Lightning; location unknown |
| 10 | 1.5 | 12 | HM | 2.8 | 0.8 | 12 | Lightning; location unknown |
| 11 | 1.5 | 26 | HM | 2.8 | 1.2 | 26 | Lightning; location unknown |
| 12 | 1.5 | 200+ | HM | 3.4 | 2.1 | 200+ | Lightning; location unknown |
| 13 | 1.7 | 79 | HM | 3.2 | 1.7 | 79 | Lightning; location unknown |
| 14 | 2.2 | 75 | HM | 4.3 | 2.1 | 75 | Lightning; line off Mio to Cook, Emery |
| 15 | 1.3 | 1 | HM | 3.0 | 1.2 | 3 | Lightning; location unknown |

H = Highly damped figure.
M = Medium damped figure.
HM = Combination highly damped and medium damped figure.
* Duration at approximately the value shown.

at which the system is solidly grounded, no records showing any appreciable rise in voltage above the maximum normal values were obtained. At East Springfield, where there is no neutral ground, voltages to ground up to about 1.5 times normal were recorded. A cumulative percentage curve showing the distribution of the voltages recorded at East Springfield is shown on Fig. 15. In preparing this curve only voltages above the maximum normal bus voltage to ground (31-kv peak) at East Springfield were used.

*Public Service of Northern Illinois—33-Kv West Zone Network.* On about January 30, 1933, the West Zone network was solidly grounded at Bellwood and Electric Junction. Oscillograph and surge recorder observations were continued for about 10 months under this operating condition. Only a few oscillograph records showing voltage above normal were obtained, the maximum being 1.2 times normal, recorded at the time of an oil bushing failure at Bellwood.

A considerable number of surge records were obtained, a majority of them being of the unidirectional or highly damped type. However, some combination figures showing evidence of dynamic overvoltage were obtained. One such figure is illustrated in Fig. 13*C*. The continuous band on this record, obtained while the film was being stepped up in position for another surge, was present on many records, both with the system solidly grounded and when grounded through neutral resistance. Cumulative percentage Curves III and IV of Fig. 14 show the magnitude distribution of the observed voltages producing figures whose medium damped portions exceeded 31-kv crest.

## Discussion

A study of the wave shape of the line-to-ground voltages sheds some light on the nature of the fault and the mechanism by which the overvoltage is produced.

Oscillograms from the isolated neutral system showing voltages over 2.6 times normal (300-kv peak) have been carefully inspected as to wave shape and found in all cases to show approximately a sine wave. In these cases the majority of the faults involved insulator flashover due to lightning and consequently arcing, but there is no evidence of the abrupt rises in voltage on the sound phase that would be expected were the fault current restriking intermittently. In a number of other instances the oscillograms indicate a self-clearing fault, with no circuit breaker operation, the condition which would be most likely to cause irregular wave traces.

The majority of the records from the Petersen coil system also show approximately sine wave shape and this was true of the maximum observed value. However, there were several records that indicated at some point during the disturbance a distorted voltage; usually where the fault was clearing, or, in a few cases, where the fault was reëstablished.

The 26-kv system of the Public Service Electric and Gas Company on which observations were made consists of 126 circuit miles of open wire and 32 miles of cable. Records from this system furnish the only cases of severe wave shape distortion having an effect on the magnitude of the larger values of dynamic voltage. A majority of the records from this system have uniform wave shape of the type illustrated in Fig. 11*A*. However, the highest voltages occurred in cases where the fault current, after becoming zero, reëstablished either every half cycle or intermittently, as illustrated by $I_N$ in Fig. 11*B*. The abrupt rise in the voltages on the sound phases through which they adjust themselves to the new state of affairs, is clearly apparent in the oscillogram. It is seen that

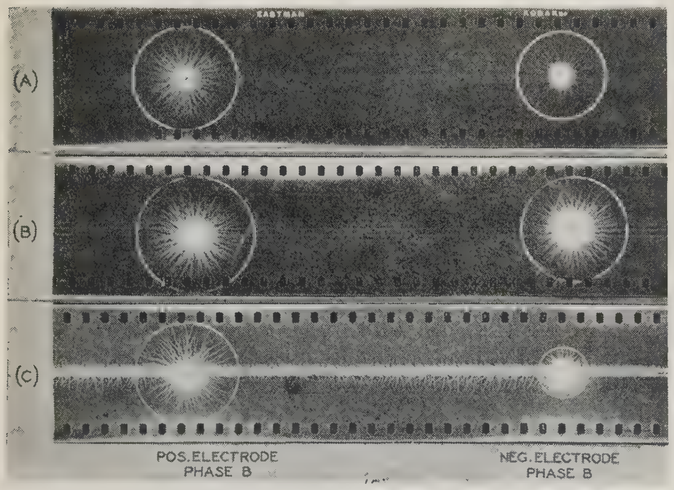


**Fig. 13. Lichtenberg figures from 33-kv West Zone network**

A. Highly damped figure. 50-ohm resistors in service
B. Combination highly damped, medium damped figure. Resistors in service
C. Combination highly damped, medium damped figure. All neutrals solidly grounded

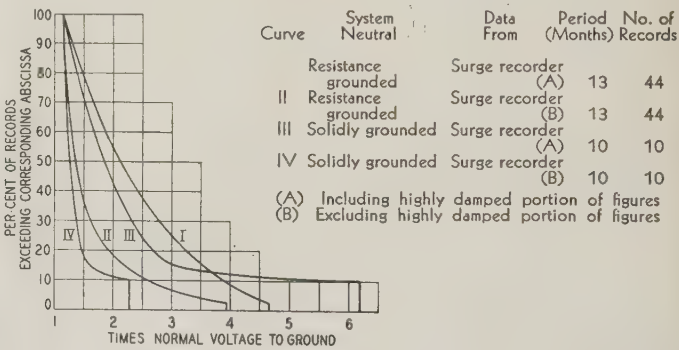


**Fig. 14 (above). Magnitude distribution of overvoltages on 33-kv West Zone network, resistance grounded and solidly grounded neutral**

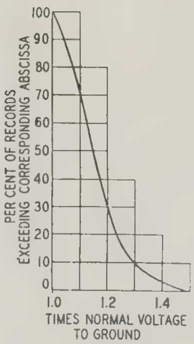


**Fig. 15. Magnitude distribution of overvoltages on 33-kv directly grounded system. Data from East Springfield oscillograph**

Period of observation 9 months (3/24/33 to 1/1/34). Total records—75

**Table IV—Classification of Records of Voltage Above 1.85 Times Normal; Public Service Electric and Gas Company 26-Kv System**

| Nature of Fault | No. of Records | Max. Meas. Voltage Times Normal |
|---|---|---|
| *Peaked Voltage Waves* | | |
| Cable failure | 22* | 2.5 |
| Oil immersed insulator failure** | 7 | 2.4 |
| Lightning | 1 | 1.9 |
| Unknown | 2 | 2.4 |
| *Sine Voltage Waves* | | |
| Lightning | 4 | 2.3 |
| Wire dropped across insulator in station by bird | 1 | 1.9 |
| Unknown | 1 | 1.9 |

* During incipient cable failure more than one record was sometimes obtained from the same source of trouble.

** All these records associated with a defective oil immersed insulator in a circuit breaker.

when the arc restrikes, the voltages of the sound phases immediately assume a value but little larger than that which they have when the arc is continuous. In this case and in others where the fault current was reëstablished every half cycle, the maximum voltage usually occurred coincident with the appearance of this particular wave shape. In none of the cases was there any indication of the cumulative building up of voltage or of large sustained oscillations in either the current or voltage waves. Table IV classifies for this system all of the records of voltage to ground above 40-kv peak (1.85 times normal) according to the wave shape and nature of the fault. It is seen that a majority of the higher voltages are associated with records of irregular wave shape and that a large number of them are associated with cable failures. All of those associated with cable failures indicate that the fault current, during at least a half cycle has become zero and reëstablished itself.

Records from the remaining systems, in general, showed sine waves with occasional irregularity due to lower harmonic frequencies.

No observations were made on systems consisting entirely or predominantly of cables, and conditions may be different from those experienced on overhead lines. For instance, there is a greater possibility of resonance conditions becoming important on a cable system where the capacitance is larger and the resistance smaller than on an overhead line. Also the characteristics of an arc on a cable may be quite different from those in open air.

The portions of the surge records obtained while the film was in motion suggest certain possibilities regarding the nature of the voltage during a fault. It will be noted that, while the film is moving, there are streamers extending from the dense band, which have the appearance of those usually associated with fairly steep wave front surges. These were noted on surge records from all systems, including the solidly grounded system, and suggest that a series of steep wave front surges frequently accompany faults. When superposed on the high fundamental frequency overvoltage measured on the isolated neutral system, it appears possible that they could account for the large medium damped figures recorded thereon.

## Summary and Conclusions

1. Sustained overvoltages larger than line-to-line voltage were frequently observed on unfaulted phases, during line-to-ground faults on systems operated with neutral isolated from ground, or grounded through substantial values of neutral impedance.

2. In general, both the maximum values and the cumulative percentage curves of dynamic overvoltage, correspond in order of magnitude to that of the neutral impedance of the systems, although the Petersen coil system and the West Zone system are partial exceptions to this.

3. The maximum dynamic overvoltage recorded by oscillographs was 3.9 times normal and by surge recorders, 5.4 times normal, both records being from the 140-kv isolated neutral system. The dynamic overvoltages on the 140-kv Petersen coil system were substantially lower, the maximum values from oscillograms being 2.8 times normal, and from surge records, 3 times normal. On solidly grounded systems the maximum value recorded by oscillographs was 1.5 times normal and by surge recorders, 2.3 times normal.

4. The maximum values of voltage quoted above represent one record only and are considerably higher than those shown by the next lower record. Only a small percentage of the voltages approached these values.

5. Comparison of the dynamic overvoltage, for the same faults, as indicated by oscillograms and surge records gives values which are in reasonably good agreement. Although the cumulative percentage curves of surge records indicate higher voltage than similar curves based upon oscillograms the 2 sets of records are not directly comparable, due to the differences in the number of records and periods of observations.

6. There has been no evidence of cumulative building up of overvoltages on unfaulted phases due to successive restriking of an arc to ground. All of the higher values of overvoltages on the isolated neutral and Petersen coil systems were essentially of sine wave shape. Periodic making and breaking of the fault current have been observed on the 26-kv system grounded through a 75-ohm resistance. Most of these faults were due to cable failures. The voltages resulting from these intermittent faults have decided peaks but their magnitudes are not much greater than the sustained value after the fault current has become constant.

7. In these investigations no observations were made on systems consisting entirely of cable; therefore, the conclusions apply only to systems where the preponderance of the circuit mileage is in open wire.

The authors wish to express their appreciation to the power companies coöperating in this study and particularly to those persons, too numerous to mention, who contributed to the installation and maintenance of the instruments and the preparation of the trouble records.

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# Discussions

## Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 15 pages appear discussions of A.I.E.E. papers received in complete and acceptable form at Institute headquarters, and subsequently reviewed by various technical committees and recommended for publication, as follows: (1) remaining unpublished discussions of 1934 winter convention papers; (2) discussions of papers presented at the A.I.E.E. North Eastern District meeting, Providence, R. I., May 16–18, 1934 (except those papers not yet published in ELECTRICAL ENGINEERING); and (3) discussions of papers on electrical communication subjects presented at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Authors' closures, where they have been submitted, will be found at the ends of the discussions on their respective papers.

Members anywhere are encouraged to submit written discussion of any A.I.E.E. paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; (3) typewritten and submitted in triplicate not later than 2 weeks after formal discussion at an A.I.E.E. meeting or convention to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

### Corona Losses From Conductors of 1.4-In. Diameter

**Authors' closing discussion of a paper published in the December 1933 issue, p. 854–60, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 470–1, and in the April 1934 issue, p. 600–1.**

**J. S. Carroll, Bradley Cozzens, and T. M. Blakeslee:** The authors are particularly pleased to note that their paper was of sufficient interest to call forth so much discussion and comment. We wish to thank those who took the time and trouble to point out certain things in which they were interested and also for the suggestions which are helpful in planning future tests.

The weather seems to be the main general topic of discussion. Would that we could control the weather in the field at the Ryan Laboratory where these experimental lines were located. Although humidity variations for the tests were between 20 and 62 per cent, the effects of the variations in this range are still negligible as it is generally conceded that the humidity factor for conductor corona loss does not become appreciable until percentages above 60 are reached. Barometric variations were also negligible, being less than 2 per cent. Temperature variations of less than 8 per cent, based on the absolute scale, existed for the tests, but since this factor was beyond control and no generally accepted correction formula is available, the data were presented as found.

The subject of corona loss during rain raised considerable comment. It must be remembered that for the greater portion of its length the proposed transmission line for which these corona loss measurements were made is to cross one of the driest sections of the United States. With this in mind the authors studied the effect of dust that might possibly be deposited on the conductors erected in the desert and reported the results. As mentioned, rain was not an important factor in the consideration of the type of conductor for the proposed line; however, every available opportunity for loss measurements during rain was made use of. Unfortunately sufficient consistent data were not obtained to justify publication. There again we could not control the rate of rainfall, size of rain drops, wind, etc., the result being that the test conditions for the different types of cables tested were not the same. Besides the observations reported in the paper concerning rainfall, it was noted that when the conductors were free from grease the rain drops on striking the surface spread out and ran to the underneath side of the conductor. This was the case even for the type *C* cable. In the case to which Mr. Peterson refers, i. e., the 1924 paper, the water drops actually stood out on the side and top of the cable. This particular cable had never been washed to remove the grease and had not been up a sufficient length of time for the grease to have been weathered off.

The majority of measurements investigating corona loss from large-diameter conductors during rain have been made at the Ryan Laboratory, and as yet no really definite conclusions have been drawn by those intimately connected with the work. It is felt that attempted conclusions based only on portions of the available data are unjustified. If any of the companies consider this factor of rain of sufficient importance to warrant the expense, from previous study it is believed to be physically possible to erect a sprinkler system over the present test line at the Ryan Laboratory which would enable the study of corona loss from different types of conductors under controlled conditions.

Along this matter of controlled conditions, a careful study is being made of some of the weather factors affecting corona loss. Some of this preliminary work is reported by Hegy and Dunlap in ELECTRICAL ENGINEERING, Feb. 1934, p. 272–3.

The matter of die grease was mentioned in all of the discussions. This was without exception the greatest difficulty in the way of making comparison of the different types of cables. Past tests have definitely shown that it is absolutely necessary to remove this grease to approximate the losses on weathered cable. The justification for this comparison is given in the author's 1933 paper (A.I.E.E. TRANS., v. 52, 1933, p. 55).

We wish to answer the comment made by Professor Harding in the second paragraph of his discussion by referring to the latter part of Mr. Peterson's first paragraph. With respect to the calculation Professor Harding makes in paragraph 4, as nearly as we can make out he is assuming that the cable showing the highest losses in the group will be operated at 330 kv, or he has selected a critical potential of 430 kv on the 1.4-in. type *C* conductor. The facts are that the latter cable was chosen for the job and the maximum operating voltage will be approximately 285 kv which, by the same process of calculation used, will show an approximate loss of 1 kw per mile of line at an elevation of 3,500 ft and desert temperatures.

As for the transfer of single-phase measurements to what would be expected on a three-phase line, we checked the method carefully with an actual three-phase set-up before attempting to use single-phase measurements to calculate three-phase losses. As stated in the paper, this method has its limitations and is not recommended where three-phase measurements are possible.

Concerning Professor Harding's point regarding the value of corona loss in the attenuation of surges with steep wave fronts, it must be remembered that the surge voltages are from 6 to 10 times normal line voltage. Corona formed by these higher voltages is little affected by minor variations in size or shape of the conductor.

In regard to the degree of accuracy of the measuring equipment referred to by Professor Harding, reference should be made to the previously mentioned 1933 paper which discusses the care taken in the actual calibration of instruments and equipment. Checks of the complete system of measurement have shown that the normal errors of reading instruments are much greater than the errors introduced by the equip-

ment itself. An example of the accuracy may be obtained from the plotted points on the insulator loss curve, Fig. 8 of the paper referred to, where values as low as 2 watts at 200 kv were recorded. It was because of this high degree of accuracy developed at the Ryan Laboratory in measuring corona loss that the City of Los Angeles Department of Water and Power felt justified in having the measurements made there.

Mr. Peterson's question of the economic feasibility of cleaning conductors resolves itself into a question of the characteristics of the weathering process. This process on a new, uncleaned conductor may cause a roughening and consequent increase in corona loss due to unequal weathering of the grease-covered surface. On a thoroughly clean conductor the weathering process is uniform over the entire surface with a consequent tendency for a reduction in corona loss. These considerations, together with the very great adverse effect of grease on corona loss demonstrated may justify the erection of cleaned conductors in transmission line construction.

While the corona loss tests reported in this paper were made possible by the Department in their thorough search for a suitable conductor for the 275-kv transmission line from Boulder Dam, it is distinctly and obviously true, as stated by many commentators on the paper, that the final choice for the transmission line was not based on corona loss measurements alone. The regular mechanical and other properties of the cable were principal factors with the Department in the cable selection. Time did not permit the thorough study of each cable surface over complete ranges of weather conditions, an investigation which would be highly desirable, but the tests were carried out primarily in the effort to determine just how much weight should be given the corona loss factor in the selection of high voltage transmission line conductors.

## Portable Schering Bridge for Field Tests

**Authors' closing discussion of a paper published in the January 1934 issue, p. 176–82, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 478–81, and in the April 1934 issue, p. 618–22.**

**C. F. Hill, T. R. Watts, and G. A. Burr:** The reasons for preferring the inverted Schering bridge are:

(a) It is direct reading and requires no correction or vector subtraction of the impedance to ground through the transformer.

(b) The shield at testing potential is a great advantage in testing transformer bushings. The difficulty of removing the transformer lead from the bushing as required by other methods has probably been the principal reason why so few transformer bushings have heretofore been tested.

The placing of the ground at $C_1R_3$ and galvanometer terminal at the left hand corner of the bridge diagram, Fig. 1, page 177, January 1934 ELECTRICAL ENGINEERING, will probably not eliminate errors due to overhead interference, because part of the picked-up interference current would flow to ground through $C_1$ directly and the rest through the parallel path composed of $C_2$, $R_4$, and $R_3$ in series.

The sensitivity of the bridge is such that an unbalance of 0.0005 in the power factor reading will give a 1-mm deflection when testing a bushing of 200-$\mu\mu$f capacitance with normal power factor. The curve in Fig. 5 is applicable to all sizes of condenser bushings.

The test method using only voltage and current readings will without doubt discover condenser bushings with broken down layers or with general depreciation far progressed. It does not give the complete analysis provided by the power factor and capacitance determination. The use of the straight Schering bridge in England for field testing was not known by the writers at the time of publication. The Schering bridge will not read the resistance of segregated wood members, but in the test procedure bridge readings are taken on the bushings with the circuit breaker open and closed and faults in the wood members are located as parallel leakages. They are traced and eliminated with the aid of a megger.

The power factor, capacitance, watts, or current can all be calculated either from the bridge method or the wattmeter-ammeter method. For our method of analysis we prefer power factor and capacitance readings as only these 2 values are necessary for complete determination of condition.

Laboratory tests would indicate that the power factor reading, coupled with the capacitance reading to show that there are or are not any punctured layers, will give a fairly consistent determination of the 60-cycle voltage that a condenser bushing will stand. We believe that when the same materials and methods of construction are used it should also give an indication of relative impulse strengths.

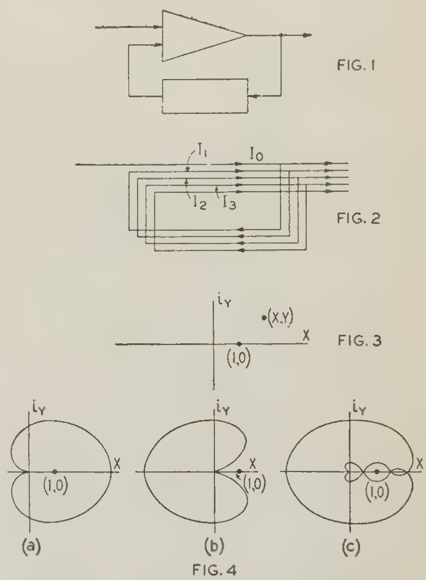
## Stabilized Feed-Back Amplifiers

**Discussion of a paper by H. S. Black published in the January 1934 issue, p. 114–20, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 461–2, and in the April 1934 issue, p. 590.**

**Harry Nyquist:** I wish to comment on feed-back amplifiers with reference to the freedom from singing. When an amplifier is constructed so that a portion of the output energy is fed back (Fig. 1) to the input, there is danger that a sustained condition of singing may occur. For the purpose of studying the singing condition, it is permissible to regard the feed-back phenomenon as a series of waves (Fig. 2). Let $I_0$ be the wave in the output of the amplifier element due to an external signaling wave when there is no feed-back included. Then this wave $I_0$ is followed by another wave $I_1$ which is the result of $I_0$ being fed around the circuit and being modified by the feed-back wave and by the amplifying element. Similarly $I_1$ gives rise to wave $I_2$ and so on indefinitely. The total wave in the output of the amplifying element due to the external signal wave is the sum of all these.

It will be convenient to use a short name for the ratio of the steady-state value of any one of these waves to its predecessor. This ratio may be called the feed-back ratio. It is the same as the quantity $\mu\beta$ in Mr. Black's paper. The feed-back ratio, being the ratio of any one of these waves to its predecessor, is generally a complex number and may be represented by a point $(x, y)$ in a diagram as in Fig. 3.

It is relatively easy to see that when the feed-back ratio is less than unity, a stable condition exists. Suppose, however, that a circuit has been constructed such that




**Conditions for feed-back amplifier singing**

the feed-back ratio is materially greater than 1, say it has the value 10, then the steady-state value of each one of these waves is 10 times as great as its predecessor and it is natural to assume that a singing condition exists. In fact, one is tempted to assume that a singing condition exists whenever the feed-back ratio exceeds unity so that each one of these waves is greater than its predecessor. Experience shows that this conclusion is incorrect, which is fortunate because the utility of feed-back amplifiers would be very much less than it is if the feed-back ratio had to be limited to values less than unity. The defect of the theory just hinted at is that it fails to take account of the building-up processes. While it may be perfectly true that each one of these waves is 10 times as great as its predecessor in the steady state, it does not follow that this is true at any specified instant because the later waves have not had time to build up to a steady-state value.

An accurate summation of these waves taking full account of the building-up processes ("Regeneration Theory," H. Nyquist. Bell System *Tech. Jl.*, Jan. 1932), leads to interesting results. Since these processes play an important rôle it is not surprising to find that the transmission properties of the whole frequency range are of importance. Briefly, the criterion which is found for stability is that if the feed-back

ratio is applied on this diagram for all frequencies from 0 to infinity, the point unity should lie outside of the locus thus formed in order to have a stable condition (Figs. 4*b* and *c*). If it lies inside, there is a singing condition (Fig. 4*a*).

It may be seen that the feed-back ratio may have any value provided it is not positive and greater than unity at the frequency where it is positive (Fig. 4*b*). It is possible to go even further than this and to assert that the feed-back ratio may be positive and greater than unity at some frequencies provided that care is taken that the point unity is not included (Fig. 4*c*). If this is done, the building-up processes will be such that singing does not occur. A qualitative description of what happens may now be stated as follows: These waves may be considered divided into three classes. In the first class are those which have reached their steady-state value substantially. In the second class are those which are in the process of building up. In the third class are those which have not yet attained appreciable values. If we limit our attention only to the first class, we should be led to the erroneous conclusion indicated above. However, if the second class is included and if the network is designed to satisfy the criterion indicated, the sum total of the second class will substantially cancel the sum total of the first class at any instant.

It is of interest to consider further the special condition which occurs in a stable circuit which has feed-back ratios which are positive and greater than unity (Fig. 4*c*). As shown in the diagram, this circuit is stable. Now, however, if the gain of the amplifier is decreased, the effect will be that the point unity will be included within the locus and the circuit will be singing. We have then the paradoxical condition that a decrease of gain in the amplifying element results in passing from a stable to an unstable condition and conversely an increase in gain results in passing from an unstable to a stable condition.

## Induction Motor Locked Saturation Curves

**Discussion of a paper by H. M. Norman published in the April 1934 issue, p. 536–41.**

**P. H. Trickey:** Mr. Norman states that his method does not cover the case where the tooth tips are saturated by slot leakage flux. I believe that this case is very important, especially for totally closed rotor slots.

I am giving below a method of accounting for saturation based on a different method of attack than that of Mr. Norman's. The data given were obtained in a rather rough manner, and not expected to be particularly accurate, but only to illustrate the method of attack.

A series of standstill readings were taken on an induction motor with closed slots, varying the current through the windings. From the readings of current, watts, and applied voltage the locked impedance, resistance, and reactance were obtained. The several components of the reactance were calculated as accurately as possible. An 0.05 opening above the rotor slot was assumed in calculating the zigzag leakage. Subtracting other components, the slot leakage was obtained as a function of current in the windings. From the slot leakage, all terms were eliminated except the slot constant and from that was subtracted the constant for that part of the slot between

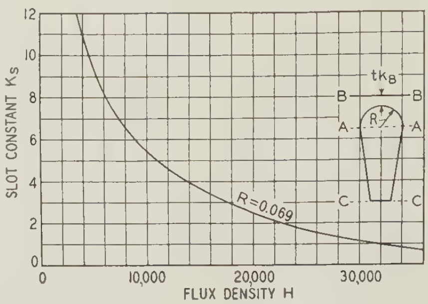



**Fig. 1. Slot constant for portion of slot between *AA* and *BB* from test assuming 0.05 opening in calculating zigzag leakage**

$H = \dfrac{CK_w\Phi I_2}{S_s W tk_B}$ where

$C$ = Total series conductors per phase

$K_w$ = Product of pitch and distribution factors

$I_2$ = Secondary locked current referred to primary

$S_s$ = Secondary slots

$W$ = Width or stacking of rotor

$tk_B$ = Thickness of closed slot bridge

*AA* and *CC* (Fig. 1) which is easily calculated.

The remainder was plotted as a function of the current in the rotor, turns, number of slots, stacking of the rotor, and the thickness of the bridge.

The results of this test are shown in Fig. 1. Obviously, there are many inaccuracies which could be overcome by more tests on enough motors to obtain a good average. However, the reactance of the saturated bridge will probably vary from 50 per cent to 150 per cent because of punching strains in the bridge unless the rotor punchings are annealed, and even then the bridge thickness will vary due to manufacturing tolerances, so that any great refinements are unnecessary. There should be a separate curve for each value of bridge radius. The figure also shows that for low values of *H*, the reactance may become very large. This would occur if the bridge were too thick or if the motor were greatly underrated.

## Switching at State Line Station

**Author's closing discussion of a paper published in the January 1934 issue, p. 148–56, and presented for oral discussion at the session on electric power switching of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.**

**T. C. White:** It is interesting that one of the problems most generally discussed is that of oil fire hazards; it so happens that we at State Line have also been giving a great deal of study to this question. Beyond doubt, this is a very serious problem, as evidenced by the numerous fires reported in late years. While no fires have occurred at this station, the hazard is well appreciated and we have endeavored to take all the precautions that experience at other plants has shown desirable.

However, when this problem is analyzed from the viewpoint of the increased hazard due to the metal-clad gear over that inherent in the standard oil filled equipment to be found in the average plant, that is, in transformers and oil circuit breakers, it is rather difficult to see how the relatively small total quantity of oil incident to the metal-clad equipment materially increases the hazard. Considering the equipment shown in Fig. 6, p. 151 of the paper, the total amount of oil located in the switchyard is about 416,000 gallons; of this amount, about 56 per cent is contained in transformers, 23 per cent in reactors, 9 per cent in oil circuit breakers, and 2 per cent in potential transformers. Only about 10 per cent is involved in the metal-clad portion of the switchgear. This latter oil is contained in a very large number of small strong enclosures, as contrasted with the large volume enclosed in relatively weak tanks in the case of transformers. The transformer oil fire at Hell Gate described by Mr. Hall illustrates the great hazards due to transformers in practically all installations. Perhaps one of the most prevalent hazards in general is in the case of potential transformers, especially at the higher voltages where comparatively large oil volumes are needed and adequate protection is difficult to provide. At State Line, however, the highest voltage potential transformers used are 22 kv. It is to be hoped that recently introduced non-combustible insulating mediums can be developed at reasonable costs; until then, oil filled equipment should be designed to contain a minimum of oil consistent with adequate clearances.

Replying to Mr. Sporn's statement concerning disastrous fires which have occurred in oil filled switchgear, we know of no case where a serious fire has occurred in equipment at all comparable with that at the State Line station.

The question of weather protection for work on the outdoor switchgear under adverse conditions in some locations may certainly be very troublesome. Whether the proper solution is enclosure in a building shell as Mr. Sanderson suggests or a construction which would be designed with the parts needing regular maintenance completely surrounded and protected by the structure of the gear is a question, but it is agreed that maintenance and to some extent operating costs would be decreased if either were done, however, as pointed out in the paper, no serious difficulty has arisen to date and it has been possible so far to schedule routine outdoor work in seasons of favorable weather. The one big maintenance item is oil circuit breaker overhauling, which is done annually. Possibly the adequacy of such a general routine may be open to some question, but so far has been entirely satisfactory. Undoubtedly the problem of scheduling such work for favorable conditions will become more difficult as equipment becomes more extensive. Emergency work may, of course, be necessary under unfavorable weather conditions, but tent-

like shelters and other temporary expedients can be used and in fact were used during construction. In weighing the advantages and disadvantages of outdoor gear such as that used at State Line, the difficulties of outdoor exposure cannot be ignored, but they must be considered in the light of the amount of regular work absolutely necessary and the probable need of emergency work.

I agree that the question of the relative advantage of duplicate buses as against a single bus with a transfer bus must be answered by consideration of the service and other conditions involved, and no set rule can be laid down.

Answering Mr. Hall's question, ground fault protection is provided at State Line and the method employed is described in Mr. Rossman's paper (reference 5) in the A.I.E.E. TRANSACTIONS, v. 49, 1930, p. 400. The degree to which sectionalized ground fault protection on metal-clad gear should be carried is almost entirely determined by economic considerations; metal-clad gear permits the use of a very selective relay scheme, both between main and reserve buses, sections of a bus, or individual phases, depending upon how many insulating joints and individual grounding transformers are supplied for the bus enclosures. In the case at State Line, it was felt that additional selectivity between main and reserve buses could not be justified economically.

In discussing generator sizes, Mr. Hall notes that Unit No. 2 is 50,000 kw smaller than Unit No. 1. Unit No. 2 is a single-element double-winding generator, taking up about half the space of Unit No. 1 and having twice the capacity of the largest of the 3 elements of that unit, that is, the electrical capacity of each winding of Unit No. 2 is about the same as that of the largest element of Unit No. 1.

Answering Mr. Sporn's criticism of the scope of the paper, perhaps it should be pointed out that the intention was to prepare the paper along the lines proposed by the committee, that is, to review the art of switching in the light of actual operating experience, showing how far the equipment actually fulfilled or fell short of the design objectives and present day requirements, incidentally pointing out its serviceability and reliability and indicated trends. I believe, however, that another symposium on this subject, covering the basic principles of future, as well as existing practice, would be very timely and desirable.

## Pantograph Trolleys I—Design Features

**Discussion of a paper by W. Schaake published in the January 1934 issue, p. 182–9, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451, and in the April 1934 issue, p. 589.**

**P. E. Wade:** Mr. Brown is to be commended for emphasizing the importance of limiting normal contact wire height to the lowest value consistent with operating safety. Some years ago the question of asking the American Railway Association to consider a standard rule prohibiting the use of box car tops by trainmen within electrified territory was debated, and dismissed as being impracticable in switching yards and on some mountain grades. Every foot removed from such height would be of great help in connection with collector design and performance and system costs. In 1914 the American Railway Engineering Association recommended a minimum clearance of 9 ft $1^1/_2$ in. between car running board and contact wire to guarantee safe conditions for trainmen giving signals with lanterns. Shortly after this the maximum box car height called for a 24-ft 2-in. wire height.

In view of these facts it is interesting to note wire heights as of today given in Table I.

**Table I—Wire Heights**

| Road | Date Installed | System Voltage | Wire Height Ft | In. |
|---|---|---|---|---|
| Virginian | 1925–26 | 11,000 | 24 | 6 |
| C. M. St. P. & P. | 1915–19 | 3,000 | 24 | 2 |
| Norfolk and Western | 1915–25 | 11,000 | 24 | 0 |
| D. L. & W. | 1930–31 | 3,000 | 24 | 0 |
| Great Northern | 1927–29 | 11,000 | 24 | 0 |
| Illinois Central | 1926–29 | 1,500 | 22 | 0 |
| N. Y., N. H. & H. | 1907–27 | 11,000 | 22 | 0 |
| Pennsylvania | 1915–34 | 11,000 | 22 | 0 |
| Reading Company | 1931 | 11,000 | 22 | 0 |

This table suggests the following comments:

1. Safety clearances specified in 1914 are not required or the movement of trainmen on box cars is restricted.
2. If not already done, the A.R.A. should cancel their 1914 clearance diagrams and approve the 22-ft wire.
3. The 22-ft wire would offer no relief, as to collector design, to roads with 24-ft wire and the existence of 2 standard heights on the same road is questionable from a legal standpoint in case of damage suits.

Mr. Brown's statement about the lack of coördination of contact system and collector design is likely to be misleading. American collector designers who deal with high speed heavy traction have always dealt with contact system design and fittings, and have fully appreciated the necessity of such coördination for all classes of work. C. J. Hixson in a 1915 A.I.E.E. paper emphasized coördination. Our designers have been called upon to furnish collectors to work with systems designed and built by the railways and also to specifications furnished by the railways. The systems involve considerable variation in design detail, workmanship, track conditions, and maintenance of overhead and track, and specifications vary as to range, head-room, collecting capacity, pan lubrication, and sensitiveness. On account of relatively long and variable intervals between electrification projects and the other variables cited it is difficult for the designing manufacturer to justify investment in improvement research, which would properly be conducted under actual service conditions in each case. Furthermore it is difficult to fix upon a definite yardstick for measuring results obtained. In other words, just what strip or pan life and minimum contact wire life are considered satisfactory in each case?

The reference to an auxiliary pantograph carrying a collector shoe is presumably made to a device similar to the auxiliary bow commonly used on European collectors. The great value of this feature has been recognized but the added weight in combination with American requirements as regards range, clearances when at or near collapsed position, collection capacity, etc., do not favor its adoption. European conditions and practice permit the use of a bow fitted with aluminum contact strip and the common use of 2 collectors, with no reserve in case of wreckage. American specifications call for a single collector meeting the demands of the locomotive or car, with all the more difficult attending conditions. Even if American railways, in common, abandoned the reserve feature, the problem would still be a difficult one. The feature is important enough to justify exhaustive coöperative study on the part of the railways and designing manufacturers.

Messrs. Pickens and Brown consider the change in wire height, due to temperature change, and the rise in wire height due to direct collector pressure, all with 300-ft structure spacing and span length, as being objectionable, and the point is well taken. They do not, however, include the vertical movement of the contact wire, in fact, the entire assembly, in spans adjacent to locomotive or cars due to load being removed from the messenger by the collectors. The resultant movement and effect on collector are dependent upon length of span, speed, weight of catenary assembly, details of messenger suspension, and collector design. This movement may add to or subtract from that due to direct collector pressure in the adjacent span ahead. A combination of 300-ft structure spacing and 150-ft catenary spans mentioned by Mr. Brown with lifting hangers may go a long way toward solving the new high speed problem. This may increase cost but it also may not be unreasonable to expect an increase to meet the new conditions.

The use of lifting hangers for smoothing out the contact wire and improving collection has been advocated in the United States for many years, and they have been and are widely used in foreign countries. The engineers of the Reading Company are to be congratulated on having the initiative and courage to install a large mileage of lifting hangers and will in time be in a position to furnish valuable information on the subject.

## Pantograph Trolleys II—Operating Features

**Discussion of a paper by B. M. Pickens published in the January 1934 issue, p. 190–4, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451–2.**

**A. M. Wright:** In view of the prevailing interest in high speed train operation, the Pickens paper is valuable as the first analysis of the mechanics of the pantograph that has appeared. If train speeds are to exceed,

80 mph the dynamic reactions between the pantograph and the contact wire become of the greatest importance, and it must be necessary to determine in advance what the behavior of the collecting system will be. To build an overhead system for operation at 100 mph, say, only to find that it is impossible to maintain contact with the wire, would be disastrous. Nothing is known of the conditions for proper stability of the contact system at such speeds. There is the well-known theory that a wave in the wire accompanies the pantograph at high speeds, but, at least in hot weather when the wires are slack, all the writer has been able to observe is a violent jiggling of the wires with certain types of construction. With other designs the wires seem to be fairly stable at all times. From observation alone, unbacked by any mechanical theory, the writer has come to the conclusion that the best system for high speed operation is the "simple" catenary with inclined catenary on curves, using wires as large as possible at as high a tension as possible.

The use of the simple catenary, comprising a single messenger and a single contact wire, raises the question of the desirability of flexibility in the hangers. American practice has been to use a loop type, or lifting hanger. The Reading Company has in operation about 87 miles of simple catenary on its main line electrified tracks near Philadelphia, over which speeds of 60 to 70 mph are regularly attained. To avoid damage due to arcing at the loop hangers, sleeves and jumpers are installed, as has been described ("The Reading Railroad's Suburban Electrification," G. I. Wright. ELECTRICAL ENGINEERING, March 1933, p. 155–61). A similar type of construction is used on the Great Northern electrification ("Inclined Catenary on the Great Northern." *Railway Elec. Engr.*, April 1928) where, however, comparatively low speeds are encountered. Experience with the simple catenary on the Reading has been eminently satisfactory at all speeds, the smoothness of pantograph operation being superior to that of the compound catenary on the same railway. No evidence of burning at the loop of the hangers has been observed after 3 years of operation. In the writer's opinion, the fear of damage to the messenger due to arcing where lifting hangers are used is unfounded, at any rate where moderate currents are collected, and where jumpers are installed. Abroad, where simple catenary is more or less standard, the practice has been in some cases to use flexible hangers, and in others to clamp the hangers to the contact wire and messenger without any flexibility. While the train speed on the Reading electrified tracks is not particularly high in regular service, test runs have shown that good current collection can be obtained with the simple catenary up to 75 or 80 mph and the indications are that the system would be satisfactory at much higher speeds.

This would appear logical, inasmuch as jiggling and vibration of the contact wires with other types of construction are undoubtedly due to reflections and reinforcements of small waves. In any contact system, the analysis is complicated by the presence of the messenger. A vertical wave traveling along the contact wire will not have a uniform amplitude from span to span, but will induce a wave in the messenger. This wave in the messenger will be reflected at the end of the span and will induce a second wave in the contact wire, traveling in the opposite direction from the first. This second wave, meeting an oncoming pantograph at high speed, may cause the contact to be broken, with resultant arcing. The use of heavy wires and high tensions will reduce the amplitude of the waves (if they exist at all) and the use of as few wires as possible will eliminate some of the reflections and reinforcements.

In designing a pantograph for high speed operation, it should not be overlooked that the power required to move the pantograph through the air can become quite large. A standard pantograph for a contact wire height of 22 ft, for example, requires 73 hp at 100 mph, indicating a pressure of 274 lb on the frame. If speeds of the magnitude that are talked of today are to be realized, it will be necessary to shroud the base mechanism and to use a special cross section for the frame members. For high speed operation, the support of the contact shoe will require special attention. It is well known that the motion of an elongated body through a fluid will generate eddies, which in some cases cause oscillations of the body. Such oscillations cannot be permitted in a pantograph shoe without destructive arcing. A perfectly designed contact system will be unsatisfactory under such conditions, and even lubrication of the shoe will be of little use. The writer does not consider that the problem of current collection at high speeds is by any means solved, and a great deal of investigation is necessary before we can lay out an overhead system, and design a pantograph to collect current from it, with certainty that successful operation will result.

The last paragraph of the paper should be studied by all who contemplate high speed electric operation. The paper would have been more interesting had the derivation of the equation for the equivalent weight been given, and it should be supplemented by a paper analyzing the motions of a catenary system under the influence of a moving pantograph.

**P. E. Wade:** The upward camber in the collector shoe is a detail of design that has merit, as claimed by Mr. Brown, and is worthy of careful study in connection with collector design. This detail is used with practically all auxiliary bows on pantograph type collectors in Europe, and probably originated with bow collectors for tramways. Its application to present American designs would require some general changes to avoid an undesirable increase in distance between line of contact and axis of pan rotation.

If the collector leaves the wire, as assumed by Mr. Brown, protection afforded by the side guard is questionable as the guard would probably be wrecked by the first pull-off or steady device encountered, or the aluminum pipe burned and sawed through, creating more trouble than the horn alone. For low approach wires, however, these guards do function, the degree of protection being dependent upon height of contact wire and collector frame design which determines the angle between guard pipe and horizontal plane. Such protection should be very much in evidence on Cleveland Union Terminals with 18.5-ft wire height, and at points of low head-room on other roads.

# Trolley Wire Lubrication Improved

**Discussion of a paper by J. V. Lamson published in the November 1933 issue, p. 771–6, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 449–50.**

**S. R. Negley:** Mr. Lamson, by means of his tests, has proved a very good case against the use of copper wearing strips on copper contact wire unlubricated. However, his statement that "operation of any electric traction system without effective lubrication obviously would be destructive, unsatisfactory and costly," cannot be accepted as being developed by these tests. Most of us having to do with the operation of electric traction systems feel that lubrication of some sort is desirable. Frequently, due to steam operation over the same tracks, we believe it unwise to use a grease which might collect grit particles from locomotive blasts and result in an abrasive substance which would increase the wear on the wire.

The Reading Company has been operating electric multiple unit cars in their suburban service for nearly 3 years, and due to the presence of steam traffic have thought it undesirable to lubricate with the lubricants ordinarily used for this purpose. Cars were placed in service with pantograph strips of rolled steel, which collect current from a 55 per cent conductivity bronze contact wire. In certain sections of the line which we have had occasion to examine, after a period of 2 years during which time the wire was subjected to 88,000 pantograph passes the wear amounted to 1 per cent of the total area of the wire. The surface of the contact wire is smooth and polished a dark brown color, giving no evidence of the excessive abrasive action found by Mr. Lamson with his tests of copper on copper.

The several other points of difference between actual operating conditions and the test set-up are as follows:

| | Reading Co. | Mr. Lamson's Test |
|---|---|---|
| Pantograph pressure per shoe per wire | 18 lbs. | 7.5 lbs |
| Material of wearing strip | Steel | Copper |
| Contact wire | Bronze, 55 per cent cond. | H.D. copper |
| Av. current collected | 70 amp a-c | 200 amp d-c |

The above table therefore, presents a wide field for additional tests, *viz.*, the effect of varying pressures, varying pantograph strip materials, and current densities per pantograph.

The effect of varying current densities may have had considerable effect in the results of Mr. Lamson's tests with the

solid graphite block, for it is conceivable that since no effort was made to insulate the block from the pantograph wearing strips, the decrease in current density may have contributed largely to the small amount of wear obtained.

The addition of a device for lubricating the contact wire in the manner suggested by Mr. Lamson tends to complicate and increase in weight a mechanism in which simplicity and lightness are paramount factors. I presume it can be shown that lubrication is desirable, but I believe the results of further tests could be made more valuable if an attempt is made to obtain lubrication by the application of dry lubricant between the pantograph wearing strips, thus eliminating additional complications to the pantograph itself.

## Shunt Resistors for Reactors—II

**Discussion and authors' closure of a paper by F. H. Kierstead and L. V. Bewley published in the March 1934 issue, p. 411–8, and presented for oral discussion at the transmission and distribution session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.**

**C. W. McGill:** There has been a wealth of calculation, testing data, and discussion stressing the increased surge voltages due to reflections and oscillations caused by the presence of inductance either in the form of choke coils, reactors, transformers, feeder regulators, or end turns of station equipment. The choke coils have been removed, the transformers have been redesigned to be "surge proof," and some of the reactors have been eliminated by changed ideas in station layout, such as more segregation, synchronizing at the load, transformer-generator units, circuit breakers of larger rupturing capacity, etc.; but there still remain many cases requiring reactors.

Surges do cause stresses and oscillations within the reactor, but external protective means are not justified with the present designs having sufficient mechanical strength, copper, and insulation.

As has been pointed out by calculation and by test, a resistor shunting the reactor tends to reduce the reflected and the transmitted surges; but, like so many other protective devices, each installation must be carefully studied to determine the economical justification.

Thus, for a station having only a few outgoing feeders, the shunting resistor does not reduce the reflected voltages, and dangerous potentials appear on the incoming line and bus. Lightning arresters on the lines would be necessary for their protection and, in turn, would also serve to protect the reactors and station equipment. The authors mention that this case may be disregarded, but there is a growing tendency to reduce the number of feeders directly connected to a bus section. Protection of the bus or station equipment in this case might be more economically obtained with bus lightning arresters or some type of wave modifier, such as a combination of shunting condenser and arrester or a Ferranti absorber. It must be kept in mind that when the voltages on both sides of the reactor, due to multiple reflections, are nearly equal, the thyrite resistor is of no aid, no matter what the value of the surges.

Stations having many feeders are not materially helped with respect to bus voltages by the shunting resistors due to the low surge impedance of the combination at the bus, but the incoming line carrying the surge receives some protection. Therefore, a comparison with arresters should be made. Considerable calculation would be required in such a study as the efficacy of the resistor reduces as the surge impedance at the station becomes smaller, as occurs with underground cable. As in other such problems, the previous history and records of faults on the station or lines in question, the type of service required, and the station design or method of operation must be considered in justifying the expense.

**F. H. Kierstead** and **L. V. Bewley:** Mr. McGill in his discussion of our paper states that "for a station having only a few outgoing feeders, the shunting resistor does not reduce the reflected voltages, and dangerous potentials appear on the incoming line and bus." Referring to Table I of our paper it will be noted that for no outgoing feeders the bus voltage is reduced by the thyrite resistor from 1.77 to 1.05; for one outgoing feeder the reflected voltage is reduced from 0.97 to 0.72 and the bus voltage from 0.87 to 0.48; for 1.8 outgoing feeders the reflected voltage is reduced from 0.95 to 0.59 and the bus voltage from 0.55 to 0.39; and for 4.3 outgoing feeders the reflected voltage is reduced from 0.96 to 0.49 and the bus voltage from 0.39 to 0.26. This is a substantial reduction in voltage for a few outgoing feeders.

Mr. McGill states that "stations having many feeders are not materially helped with respect to bus voltages by the shunting resistors due to the low surge impedance of the combination at the bus, but the incoming line carrying the surge receives some protection." With many feeders and the proper thyrite resistors an impulse voltage passes through without appreciable reflection. Therefore, the impulse voltage on the feeder side of the reactor is reduced to approximately half the value it would have had if it had not been shunted by a resistor.

Mr. McGill also states that "protection of the bus or station equipment in this case might be more economically obtained with bus lightning arresters." It is true that more complete protection can be obtained by lightning arresters but at considerably greater expense, since the thyrite resistor is a very inexpensive device and, being installed in the center of the reactor, entails no installation charges. It should be realized that an arrester connected to the bus does not limit impulse voltages on the feeder side of the reactor and therefore to obtain protection on this side of the reactor with arresters it is necessary to install an arrester on each feeder. However, by shunting the reactor with a thyrite resistor a large measure of protection is obtained. The resistor thus permits the bus arrester to afford a much more extensive protection to the system.

Summarizing, the shunt thyrite resistor should not be used in lieu of but as a very effective supplement to the bus arrester.

## Theory of Primary Networks—Part II

**Discussion of a paper by F. M. Starr published in the March 1934 issue, p. 426–31, and presented for oral discussion at the transmission and distribution session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.**

**C. A. Corney:** It is believed that this paper will tend to dispel some of the uncertainty that has existed in the minds of those interested in the question of emergency unbalanced loading of network units with respect to its effect upon reserve transformer capacity. Certain limits have been established in the first portion of this paper which will serve as a guide in any economic evaluation of this subject in making comparisons with other methods of supply.

It is of interest to note that with, say, 4 per cent impedance mains, small network systems up to 8 units may be designed to balance the load evenly among the remaining units with one feeder out of service. In the larger systems, if feeders are interleaved, a 10 per cent maximum increase in load on any one unit may be expected with one feeder out of service, and if not interleaved, that is, if adjacent units are supplied from the same feeder, a maximum increase of about 30 per cent may occur. In actual practice the possibility of providing a certain amount of interleaving will likely occur accidentally so that the increase in load which might be expected can be assumed to lie somewhere between the limits of 10 per cent and 30 per cent.

It has been stated that bus differential protection can be provided if needed. It might not be amiss, however, to point out that it would be desirable before doing so to examine carefully the possibility of incorrect operations occurring on through faults because of the breakdown of current transformer ratio on high currents. In connection with this general type of protection, it would be extremely helpful if manufacturers would have available standard current transformer ratio curves up to 50 times full load or even more, instead of up to 10 or 15 times, as now supplied.

It has been fairly well demonstrated by operating experience that the relay equipment now available is adequate to provide proper selection when applied to a network system. There may be some doubt, however, as to the efficacy of the instantaneous reclosing cycle now being advocated when applied to a network system, inasmuch as the switch at one end of the network feeder might complete its round trip before the breaker at the other end opened, in which case there would be no initial interruption of the arc.

In considering the question of the coordination of fuses with relay settings, the relay equipment of network units may be required to conform to a particular relay curve having somewhat different characteristics from the present relay operating curves, in order to permit the various transformer and branch fuses to clear the trouble with the minimum circuit interruption. This phase of the network protection problem should be given careful thought by the designers of this equipment.

In connection with the derivation of the short-circuit current values on a network,

it may be of interest to remark that our engineers working independently on a particular problem obtained by the longhand method of calculation a value of 5,750 amp, and by means of the calculating table a value of 5,500 amp, which is a sufficiently close agreement for all practical purposes.

## A Graphical Solution of Steady State Stability

**Author's closing discussion of a paper published in the April 1934 issue, p. 566–8, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.**

**H. B. Dwight:** In reply to an inquiry as to why an adjusted value of synchronous reactance should be used: The reason is that it gives results which are usually nearer to measurements than those given by the "unsaturated" value of synchronous reactance, obtained by short-circuiting the machine at its terminals.

**Table I—Maximum Power**

| | Unsaturated Sync. React. and Sat'n. Curve | Adjusted Sync. React. and Sat'n. Curve | | Unsaturated Sync. React. and Air Gap Line |
|---|---|---|---|---|
| | kw | kw | kw | kw |
| Two dupl. mach........ 8 amp f.c. Table I[1] | 136 .. | 260 .. | 287[4].. | 377 |
| Two dupl. mach........ 9.4 amp f.c. Table III[1] | 86 .. | 146 .. | 137 .. (Test) | 304 |
| Gen., sync. cond., and load[2]........ | 50,000 .. | 81,300[3].. | 80,400[5].. | 170,000 |

1. A.I.E.E. Trans., 1926, p. 1.
2. A.I.E.E. Trans., 1924, p. 98.
3. *G. E. Review*, Dec. 1932, p. 614.
4. Calculated by Nickle and Lawton.
5. Calculated by E. B. Shand.

In Table I are shown 3 cases of maximum power, each calculated by 3 ways of using synchronous reactance. The first, and oldest way is to use the "unsaturated" value of synchronous reactance, and to take the excitation voltage from the no-load saturation curve. The second way is to use adjusted synchronous reactance as in Appendix A of my paper, and the third way is to leave out saturation completely, using the unsaturated synchronous reactance and taking the excitation voltage from the air gap line. The first way gives too small a value of maximum power and the third way gives too large a value, unless the field current is small, such as that required for no load.

Other useful problems are to calculate the power angle and the rate of change of power angle. However, if a method of calculation gives an error in the maximum power, it will almost inevitably give a similar error in other power calculations. For instance, the curve of kilowatts and angle for a uniform air gap machine is often practically a sine wave, and if the height of the sine wave is 40 per cent too great, then all other readings from the curve will be 40 per cent too large.

The complete vector diagram involving armature ampere turns cannot be used directly if the field current is specified in advance. Methods of solution of steady-state problems by families of curves, as used by E. B. Shand and Nickle and Lawton in the papers referred to in Table I, and by O. G. C. Dahl in his book "Electric Circuits," have good accuracy, as has also Professor Dahl's synchronous reactance method described in Electrical Engineering, April 1934, p. 604. A method will shortly be published by C. Kingsley, of Massachusetts Institute of Technology, which does not sacrifice accuracy and which gives good promise of shortening the time of computation materially.

The alternative method of computing the general contents of a transmission system, published in A.I.E.E. Trans., v. 41, 1922, p. 781–4, and mentioned in my paper, is for series connections and not for the calculation of branches in parallel.

## Irregular Windings in Wound Rotor Induction Motors

**Discussion and authors' closure of a paper by R. E. Hellmund and C. G. Veinott published in the February 1934 issue, p. 342–6, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.**

**P. L. Alger:** I have been interested in the theory of irregular polyphase windings for many years, and have tried to develop systematic methods of determining the optimum distributions for least reactance, least magnetic vibration, least unbalance, and least stray load losses. Prof. A. A. Bennett has worked with me in this field, and has derived some very interesting results, but we have never been sufficiently satisfied with their form to publish them.

Of the published methods for calculating the differential leakage reactance, I have found that given by Chapman in his "London Electrician" article of 1916 the most satisfactory, as developed (p. 508) in my paper "The Calculation of the Armature Reactance of Synchronous Machines" in the A.I.E.E. Trans., v. 47, 1928, p. 493–513. My conclusions at that time were that the differential leakage for a regular 3-phase winding is best calculated by formula 17a, and that the leakage for an irregular balanced winding can be taken as roughly twice that given by this same formula (p. 503). This formula gives for the regular 6-pole, 3-phase, 36-slot, $^5/_6$-pitch stator winding of the motor described in this paper a differential leakage reactance equal to

$$X_D = \left(\frac{13\pi^2}{9}\,\frac{\sin^2\frac{\pi}{12}}{\sin^2\frac{5\pi}{12}} - 1\right)X_M = 0.023X_M$$

where $X_M$ is the magnetizing reactance of the motor per phase.

For the balanced, irregular, 27-slot, $^8/_9$-pitch rotor winding, the formula gives

$$X_D = \left(\frac{425.2\pi^2}{486}\,\frac{\sin^2\frac{\pi}{9}}{\sin^2\frac{8\pi}{9}} - 1\right)X_M = 0.040X_M$$

and we may take twice this, or 0.080 $X_M$, as the expected result.

For the irregular, unbalanced, 24-slot, full pitch rotor winding, the formula gives

$$X_D = \left(\frac{178\pi^2}{243}\sin^2\frac{\pi}{8} - 1\right)X_M = 0.058X_M$$

The fact that this winding is unbalanced as well as irregular will appreciably increase the differential reactance, so we may arbitrarily take the expected result as 2.5 times this, or 0.145 $X_M$.

From the test power factor and impedance results given in the paper, I estimate the no-load current of the motor must have been close to 2.5 amp, giving a magnetizing reactance per phase wye of 52 ohms. On this basis, the total differential leakage reactance of the motor with the 27-slot rotor in place should have been

$$(0.023 + 0.080)(52) = 5.4 \text{ ohms}$$

and with the 24-slot rotor

$$(0.023 + 0.145)(52) = 8.7 \text{ ohms}$$

which compare with the total reactance values derived by the authors from breakdown torque tests of 6.6 and 9.8 ohms, respectively. The relatively small slot and end leakage reactance, which should be the same for both rotors, readily accounts for the difference of 1.2 ohms between the calculated and test results.

No claim is made that this method of calculating the differential leakage reactance is accurate, since the arbitrary factors of 2 and 2.5, respectively, are used regardless of the many variations in winding distribution pattern that can be selected. The check is sufficiently close, however, to show that the previously published article affords a practical means of estimating the performance of such irregular windings.

**C. J. Koch:** Although the subject of irregular windings has received considerable attention in the past, the same study has not been extended to those windings which are unbalanced as well as irregular. The present paper constitutes an addition to this study.

When the number of poles, slots, and phases is such that the winding will be unbalanced as well as irregular, there are a great many possible groupings of the stator coils. In the past the designer has usually striven to arrange this group so that the 3 phases are as nearly as possible displaced 120 electrical degrees from one another.

There is a growing realization that a winding so distributed is not always the best, as it is often more desirable to minimize the additional differential leakage reactance and to minimize the noise.

In general, the differential leakage reactance of any winding may be defined as the sum of the magnetizing reactances of all the harmonic fields produced. As an alternative to the method described by the authors, the additional leakage reactance of an irregular winding may be calculated by determining the pitch and distribution constants of all harmonic fields produced, and then summing up their magnetizing react-

ances. This method is somewhat laborious but it has the advantage that it gives at the same time an idea of the relative magnitudes of the harmonic fields that will be present. This is a decided advantage in passing judgment on the noise qualities of the motor which will result. For example, in laying out a 12-pole, 120-slot, 3-phase winding, from the point of view of quiet operation, it is much more important to minimize the 8-, 10-, 14-, and 16-pole fluxes than it is to balance up the 3-phase currents exactly.

At the present time, when the designer is being called upon more and more to improve characteristics without the use of additional material, and to reduce the noise produced by motors, there results a growing tendency to increase sufficiently the variety of punchings used to eliminate windings of the irregular unbalanced type.

**C. G. Veinott:** Mr. Koch and I are in complete agreement on the fact that the presence of only a slight voltage unbalance in an irregular winding is not a reliable indication that the winding is satisfactory and also we are in agreement that there is a growing tendency to discontinue the use of irregular unbalanced windings.

Mr. Koch, by his definition, includes the zigzag leakage in the differential leakage. There has been much confusion on this subject because some authors do not include the zigzag leakage and others do. Mr. Alger, in his 1928 paper on synchronous machine reactance, considers air gap leakage as being made up of 2 components, namely, zigzag leakage and belt leakage.

Mr. Hellmund and I have brought out that in the case of irregular windings, there is yet a third component of the air gap leakage which, to our knowledge, has never before been mentioned in literature. This might well be called irregular distribution leakage; and how to calculate its exact magnitude may well be left for future investigation.

The following distinctions between the 3 components of air gap leakage should be noted. Zigzag leakage varies cyclically through a slot pitch (unless the effect is averaged out by skewing). Belt leakage, as commonly understood, varies cyclically through a phase belt. The irregular distribution leakage varies cyclically through a greater distance; it may be a pole pitch or even a complete revolution of the rotor, if both windings are irregular. Another distinction is to be noted: while zigzag and belt leakage vary with rotor position, they do not unbalance the phases as does irregular distribution leakage. Irregular distribution leakage is present in both the 27-slot irregular balanced winding and the irregular, unbalanced 24-slot winding though, in the former case, for practical purposes it is negligible.

Mr. Alger mentions his formula for calculating the differential leakage of a regular polyphase winding, a formula he developed in 1928 for his paper on synchronous machine reactance. I think he must have made a slight error when he calculated the differential leakage coefficients for fictitious regular 27-slot and 24-slot windings, for his figures of 0.040 and 0.058 would apparently indicate a difference of 45 per cent in differential leakage due solely to this slight difference in number of slots and chording. I compute coefficients of 0.0500 and 0.0587 for the 27- and 24-slot windings, respectively, when I use his formula.

Mr. Hellmund published figures on differential leakage coefficients in regular polyphase windings in his E.T.Z. article of 1909 (see reference 5). In this article, Mr. Hellmund does not include the zigzag as a part of the differential leakage. I calculated the zigzag leakage by means of Adam's formulas (see reference 1) in order to compare Mr. Alger's and Mr. Hellmund's figures. An interesting comparison of the total air gap leakage coefficient as computed by the separate methods of Adams in 1904 and Hellmund's in 1909 with Alger's formula published 19 years later is given in Table I.

**Table I**

| | With 27-Slot Rotor | With 24-Slot Rotor |
|---|---|---|
| Zigzag coefficient (Adams) | 0.0550 | 0.0680 |
| Belt leakage coefficient for stator (Hellmund) | 0.0055 | 0.0055 |
| Belt leakage coefficient for rotor (Hellmund) | 0.0070 | 0.0075 |
| Total air gap leakage coeff. (Adams & Hellmund) | 0.0675 | 0.0810 |
| Diff. leakage of stator (Alger) | 0.0230 | 0.0230 |
| Diff. leakage of rotor (Alger) | 0.0500 | 0.0587 |
| Total air gap leakage coeff. (Alger) | 0.073 | 0.0817 |

The check is truly remarkable! The figures given by Hellmund and Adams show that in these cases more than 80 per cent of the "air gap leakage" is due to zigzag. Mr. Alger's figures show that in both cases, the rotor contributes twice as much as the stator to the "air gap leakage."

I do not think that any multiplying factor should be applied to the 27-slot winding but that Mr. Alger's suggested figure of 2 might be applied to the 24-slot winding. On this basis, I find the calculated leakage reactances in ohms to be as follows:

| | 27-Slot Rotor | 24-Slot Rotor |
|---|---|---|
| Magnetizing reactance | 47.40 | 44.20 |
| Slot & End Leakage | 2.54 | 2.74 |
| Stator "diff. leakage" (Alger) | 1.09 | 1.02 |
| Rotor diff. leakage | 2.37 | 5.20 |
| Total | 6.00 | 8.96 |
| Test Reactance | 6.60 | 9.85 |
| Difference | 0.60 | 0.89 |

The slight difference between tested and calculated results is more than explained by the skewing of the rotors. So, therefore, the additional results given above further corroborate our conclusions given in the paper that the differential leakage of the 27-slot winding, despite its irregularity of distribution, is not appreciably different from what it would be if it were a regular winding in 27-slots, but the 24-slot winding has a large component of differential leakage which would not be present in a regular winding. The paper gives means for predicting when large additional leakage is to be expected and some idea, by comparison with the differential leakage for an equivalent regular winding, how large this additional leakage may be.

# Stray Load Loss Test on Induction Machines

**Discussion and authors' closure of a paper by T. H. Morgan and P. M. Narbutovskih published in the February 1934 issue, p. 286–90, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.**

**P. L. Alger:** I welcome this paper, as I believe the college laboratories can contribute much to the electrical industry by undertaking more searching and making analytical measurements of the power losses in machinery. Under the pressure of commercial requirements in industry, there is a tendency to be impatient of details, and to rest content with superficial methods so long as there is no obvious commercial advantage to be gained by greater precision. The student seeking knowledge regardless of its immediate commercial value, by examining into details of the most familiar processes, can often discover more new and useful information than by any amount of searching in entirely new fields.

Professor Morgan's paper is particularly timely, as it is presented just when committees of the N.E.M.A. and the A.I.E.E. are endeavoring to formulate a test code including practical methods for measuring stray load losses in induction machines. Up to the present time, these very elusive losses have been neglected in the Institute Standards, simply because there was no convenient means of determining them. While the value of stray loss found in the motors tested by the authors is very much higher than in usual designs, the fact that stray load losses of 1 per cent in large machines and up to 4 per cent in small motors are commonly present shows that it is desirable to include them in all efficiency determinations.

There are 2 fundamentally distinct methods of measuring stray load loss. One is to measure the loss exactly as it occurs under operating conditions, by means of input-output or other direct loading tests. All such methods involve difficulties and inaccuracies, because the result must be obtained by measuring a small difference between the quantities. The simple dynamometer test, in which the motor input is measured with wattmeters and its output by torque and speed measurements, involves numerous sources of error and is satisfactory only for small machines. By repeating the dynamometer test with power flow reversed, using the motor as a generator, and averaging with the results of the motor test, the errors can be greatly reduced. In this way, for example, if the mechanical power as measured is too low, or the electrical power too high, the motoring losses will be higher and the generating losses lower than their true values, but the average will be closely correct. By the authors' pump back scheme the errors are further reduced, since all power measurements are made with the same meters. In our experience, the greatest accuracy with direct measurements has been obtained by a pump back test, in which the duplicate machines are rigidly connected on the same shaft and

are fed from two sources of power of slightly different frequencies.

A fundamentally different method is to measure exactly an artificially produced loss that is nearly the same as the actual stray load loss. This can be done, for example, by measuring the rotational loss produced when the machine is excited with direct current and separately driven. This "short circuit core loss" method is used with excellent results on synchronous machines, and in our experience has been found very satisfactory for induction machines also. Tests have indicated in fact that the stray load loss produced by a given current is very nearly the same over a wide range of impressed voltage and flux of the machine.

While the layman will naturally prefer the former method, thinking the test inaccuracy less objectionable than an unknown discrepancy between the real and the equivalent loss, the designer will often prefer the latter method, which gives a definitely repeatable result.

The new test code in process of formulation should rightly include each of these methods of test for use and its proper range of application. It is to be hoped, therefore, that others will follow Professor Morgan's example of making directly comparable tests by various methods, so that the industry may soon develop confidence in and actually adopt stray load loss measurements as a regular part of efficiency determinations.

**P. M. Narbutovskih:** I would like to make a few comments concerning the method of dividing the stray load loss between the 2 machines. Of the 2 methods suggested in the paper, the graphical one is the most accurate for, assuming an accurate draftsmanship, any desired precision in the final curve $E$ (Fig. 2) can be obtained by successive approximations; yet in engineering practice it may appear somewhat long and cumbersome. Besides, it requires a continuous curve representing the stray load loss as a function of the sum of machine currents. In view of this the remarks I wish to make concern the value of the numerical method suggested in the paper, where the stray load loss is assumed to be proportional to the square of the load current. This method is quite simple and the stray load loss can be divided even if only one value of it for some particular value of load is available.

On the basis of the above assumption the division of load between the 2 machines can be obtained from the following relations: for certain values of the motor load current ($I_m$), and the generator load current ($I_g$) let the value of the stray load loss in both machines be $A = L_m + L_g$. Then we can write 2 simultaneous equations:

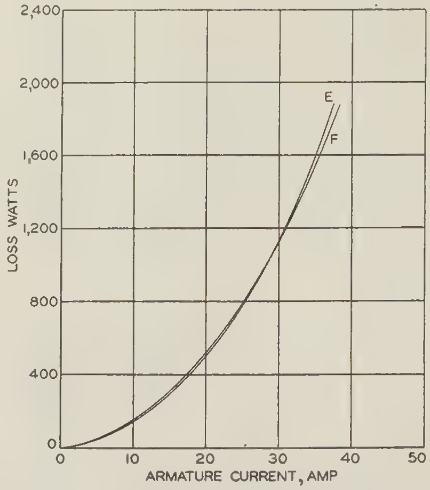
$$L_m + L_g = A$$

$$\frac{L_m}{L_g} = \frac{I_m^2}{I_g^2} = K^2$$

Solving these equations for $L_m$,

$$L_m = \frac{AK^2}{1 + K^2}$$

A curve of the stray load loss (curve $F$) as a function of current obtained by this method is shown in Fig. 6. Curve $E$ is obtained by the graphical method as described in the paper, and is plotted here for comparison. As may be seen from the graph, the difference between the 2 curves is quite small. Expressed numerically it is of the order of 50 watts maximum for the




**Comparison between curve of stray load loss obtained by 2 different methods**

highest load, which constitutes approximately 3 per cent of the stray load loss, 1.7 per cent of the total loss, and 0.5 per cent of the motor efficiency. It appears that, for the particular motor considered, the discrepancy is within the limits of engineering accuracy. In case of motors with a low value of stray load loss the numerical method of loss division will, in all probability, give practically the same value of motor efficiency as a graphical one. To reach a more definite and more general conclusion concerning the validity of the numerical method of loss division, more tests with motors of various sizes and types are necessary.

## Transformer Reactance and Losses With Nonuniform Windings

**Discussion and authors' closure of a paper by H. O. Stephens published in the February 1934 issue, p. 346–9, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.**

**A. Boyajian:** Judging by the eminently readable style of the mathematical paper by Mr. Stephens (with not a single equation in it), one would hardly suspect the fact that it is a major contribution to the mathematics of reactance and as such, deserves to be studied in academic halls just as much as in engineering offices. It opens up a new field of mathematical research for engineering instructors and students, and may well form the subject matter for many theses. I wish, therefore, to make some comments that may be helpful to those who may wish to undertake such research.

The method of calculation outlined by Mr. Stephens is not merely some little trick applicable to leakage reactance of concentric transformers, but is a method broadly applicable even to the self-inductance problems in which there is apparently no question of leakage between 2 coils carrying opposite currents. For instance, if a solenoid is wound like a helix with considerable pitch, so that the space between adjacent turns may not be ignored in the calculation of self-inductance, or again, if a cylindrical winding consists of a stack of disk coils with ventilating ducts between the disks, the effect of the gaps on the self-inductance of the winding can be calculated by resolving the winding into 2 components, one a uniform solenoid with no gaps, the other an interleaved transformer with alternate positive and negative ampere turns, in accordance with the method outlined in the paper. If classical methods are attempted, the calculation is very complicated, the complication increasing with the square of the number of the breaks in the solenoid.

It is noteworthy that Mr. Stephens' method is particularly simple and attractive for numerical work in precisely those cases in which mutual inductance formulas would be most laborious. The converse is also true. Thus, when the cylindrical winding has considerable thickness, mutual inductance calculations for the different portions of the solenoid are extremely laborious, while leakage inductance calculations are relatively simple; whereas, if the cylinder is very thin, mutual inductance formulas would not be so laborious to apply, while accurate leakage inductance calculation would be made difficult.

In order to avoid futile efforts at impossible applications, it may be well to point out that the very heart of the method is the resolution of the magnetic field into 2 mutually perpendicular components. Consequently, the method *in its simple form* is not applicable if it is attempted to obtain 2 concentric components (or 2 interleaved components). The justification of the method in simple terms is that there can be no mutual effect between 2 components whose axes are at right angles to each other. This condition cannot be satisfied unless one component is axial, the other transverse. But if 2 concentric (or 2 interleaved) components are attempted, their axes will be parallel, and there will be mutual reactance between the 2 components, which must be calculated and included in the total reactance.

This method is found particularly useful whenever magnetic materials (like transformer core) are in the neighborhood of the coils; it is so very much easier to take into account such effects on longitudinal and transverse components, than on the unsymmetrical coil arrangement directly.

An interesting and useful academic problem would be to determine the formal limits or conditions of the validity of the method as a broad mathematical method. Another interesting theoretical problem would be to analyze the transverse component of the magnetic field of a simple cylindrical finite solenoid in terms of Mr. Stephens' conceptions, and develop or reformulate appropriate inductance formulas.

**E. A. Church:** It would be of interest to operating engineers to have a simple formula, even though it may only be approximate, for determining the copper

loss in transformers operating on various tap connections when the copper loss on full winding only is known. Such a formula is suggested as follows:

$$P = X(P_1/X^2) = P_1/X$$

where

$P$ = rated load copper loss in tapped winding
$P_1$ = rated load copper loss in full winding
$X$ = fraction of winding in operation

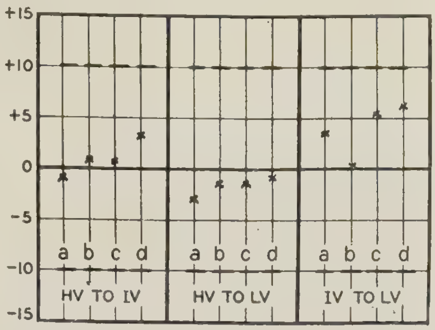
The above formula neglects any eddy current losses in the inactive part of the winding, or any change in eddy current losses in the active part caused by the irregularities of the windings.

It would be of interest to have the author give an opinion as to the maximum error which would be likely to be made by using the above formula or suggest one which would be more accurate and yet could be applied with a reasonable amount of labor.

**H. B. Dwight:** The "cross-flux" method of H. O. Stephens is a very ingenious and useful way of dealing with transformers. While it is characterized by simplicity, its accuracy has been tested by longer alternative calculations. It improves the calculation of reactance and eddy current loss of practical transformers for which apparatus there is distinct necessity for this type of calculation. It does more than that, for it leads directly to the device of thinning out the turns opposite the tap sections, as illustrated in Fig. 4 of Mr. Stephens' paper, and in this way the cross flux method leads to improved apparatus as well as to improved calculations.

**A. N. Garin:** In common with many other impedance problems, the problem forming the subject of this paper can be analyzed using 2 fundamentally different methods, the so-called "field" and "circuit" methods. The paper itself and the discussions by A. Boyajian and by Prof. V. Karapetoff employ the "field" method of attack, which is well suited for the purpose of visualizing the physical phenomena responsible for additional reactance and eddy current losses. If, however, a quantitative analysis is desired, the "circuit" method of attack may be found to be preferable. Thus, it can be shown that in addition to the concentric and interleaved components taken into account by H. O. Stephens' method, the total or effective reactance of concentric windings with nonuniform ampere turn distribution contains what may be called a "diagonal" component. While the concentric and the interleaved components are always additive, the diagonal component may be either additive or subtractive. The absolute magnitude of the diagonal component depends on the proportions and configuration of windings and for winding arrangements considered in the paper it is negligibly small. This establishes both the validity of H. O. Stephens' method of reactance calculation when applied to concentric windings with nonuniform ampere turn distribution and its limitations when applied to other groupings of windings.

From a practical standpoint the importance of the method suggested by Mr. Stephens lies in the fact that no matter how unbalanced and nonuniform the distribution of ampere turns in concentric windings, the reactance and the eddy current losses can be calculated with good engineering accuracy using only well-known and very simple formulas developed years ago for uniform concentric and interleaved windings. Only in exceptional cases, when still higher accuracy is desired, recourse must be had to more elaborate methods.




**Per cent deviation of tested from calculated reactances showing accuracy of H. O. Stephens' method of reactance calculation as applied to 2-winding reactances of a 3-winding transformer with taps in all windings. Standard N.E.M.A. tolerance for 3-winding transformer: ± 10 per cent**

a. Both windings connected for maximum turns
b. Primary maximum turns; secondary minimum turns
c. Primary minimum turns; secondary maximum turns
d. Both windings connected for minimum turns

The accompanying figure gives an idea of the accuracy of reactance values calculated by H. O. Stephens' method. The deviations of tested from calculated values are seen to be well within the standard N.E.M.A. tolerance for impedance of 3-winding transformers. In any reactance calculation there must be of course a comfortable margin between the accuracy of calculation and the maximum permissible deviation of tested from desired values because neither commercial tests nor the mechanical assembly of transformers are mathematically exact.

**H. H. Wagner:** The calculation of the leakage flux circuit in transformers and of its effect on the reactance and eddy current loss has been, perhaps, the most elusive problem of transformer designers, and only gradually have the methods of such calculation been developed and improved. In this paper, Mr. Stephens has made one of the most important and practical contributions to transformer literature in recent years. His unique method of resolution of leakage flux into 2 perpendicular components should find wide application among transformer design engineers, since the circular concentric coil construction is used in the majority of modern power transformers and is rapidly coming into favor also in distribution transformers. The paper, appropriately, points out in a concise and clear manner some of the fundamental differences in the concentric and interleaved types of construction, and some of the basic reasons why a concentric transformer is inherently more rugged and simple than an interleaved transformer.

Although the method of reactance calculation is quite comprehensive, I believe that Mr. Stephens might be a little more specific in the application of interleaving reactance calculation, particularly with reference to obtaining the length of leakage path, since the conventional formula for this is usually not so accurate with the long and slender proportions of the "interleaved groups" which would occur in this method applied to the concentric winding. However, it is evident that a considerable per cent of error in the interleaved component would usually result in only a comparatively small error in the total reactance value since the interleaved component will usually be of the order of 10 per cent of the total reactance.

It seems that mention might also be made of what value to assign to the thickness of barrier between the interleaved groups; it would appear to be logical to use a value of zero for this term in the conventional formula.

I believe that there is an error in the ratio given in step 5 of the method originally published; if the interleaved reactance component is calculated by using the total turns in the winding, it should be multiplied by the ratio $\left(\frac{\text{interleaved effective turns}}{\text{total effective turns}}\right)^2$ in order to convert it into percentage of line voltage.

**H. O. Stephens:** Mr. Boyajian's suggestion that a similar method of calculation might be used to determine the inductance of a solenoid or reactor having nonuniform distribution of turns and with appreciable radial build of windings appears to be sound. With equally accurate formulas for self- and mutual-inductances and for reactance of interleaved windings it appears that the conventional method and the proposed method would yield equally accurate results. In order to check the accuracy of the method suggested by Mr. Boyajian, as applied to inductance I took the simple case of a 3-phase reactor with the phases coaxially mounted but connected in series and considered as one single-phase reactor. The insulation breaks between the middle and end phases constitute the irregularity. The calculated inductance by the conventional method was 1.2 per cent higher than the tested inductance and the calculated inductance by the proposed method was 0.8 per cent below the tested inductance. Either method is sufficiently accurate for all practical purposes and the method to be selected would probably be decided principally by the relative familiarity of the calculator with the 2 methods as well as the degree of irregularity of the winding of the reactor.

Mr. Church suggests a simple formula for determining the impedance loss of a transformer operating with one of its windings connected on a tap when the impedance loss is known only for the full windings.

Any formula which does not take into account the peculiarities of the design, the irregularities of the windings, and the eddy current and stray losses can give only a rough approximation of the true losses. However, where operators desire this information quickly extreme accuracy probably is not required and the following formula will give a rough approximation of the required losses:

$$W_T = \frac{XW + W}{2X}$$

where

$W$ = impedance watts on full windings
$W_T$ = impedance watts on desired tap
$X$ = fraction of tapped winding in operation

This formula assumes that the impedance losses are equally divided between the 2 windings (seldom correct) and that the eddy current and stray losses are the same proportion of the total impedance watts on the tap as on the full winding (also seldom correct).

Mr. Garin's extreme case of the 3-winding transformer reactance shows that the method may be used to give commercially accurate results even for great irregularities, and it is very gratifying to find that this simplified method yields such accurate results for extreme irregularities.

In preparing the paper all reactance formulas have been purposely omitted. There are so many details to cover that the paper otherwise would have been hopelessly involved and probably less valuable. The paper presupposes that the designer has proper formulas for the calculation of interleaved and concentric reactances and that these give proper weight to long slender and short thick coils. In most cases the thickness of the barriers between the groups of the resultant interleaved components will be zero as Mr. Wagner suggests. Step 5 on p. 347 is correct for the conventional formulas that I use, which give the reactance in per cent of the voltage considered. The paper gives the method to be employed in resolving the reactance into the concentric and interleaved components. The designer must rationalize the method to suit his particular reactance formulas.

Professor Karapetoff has suggested that unless one were very familiar with calculating transformer reactances he might be very much at sea in attempting to apply the proposed method. This is absolutely true. The method presupposes a thorough knowledge of the conventional methods of calculating interleaved and concentric transformer reactances so that the designer may use good engineering judgment in applying the proposed method. Professor Karapetoff also has suggested that the method might be used to advantage in determining the reactance between certain unbalanced windings of induction motors. There are so many points of similarity between transformer and induction motor theory that one is tempted to extend the methods employed in calculating one over to the other. In this case I would prefer to leave the answer to this question to the induction motor designer who undoubtedly has short cut methods of his own to solve his particular problems.

# Distance Relay Action During Oscillations

**Discussion and authors' closure of a paper by E. H. Bancker and E. M. Hunter published in the July 1934 issue, p. 1073–80, and presented for oral discussion at the selected subjects session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.**

**F. J. Adams:** This paper will be of considerable value to operating engineers in determining whether or not their systems can be satisfactorily protected by distance relays. The paper points out that there are conditions under which distance relays, as now used, may cause undesired breaker operations, during system swings or oscillations. It also suggests ways of overcoming this difficulty. One cannot avoid the feeling, however, that distance relays are not the ultimate solution of transmission line protection. The idea of some sort of differential relaying, using pilot wires or carrier current pilot circuits, still seems to offer some hope. Is it not possible that the development of thermionic vacuum tubes may lead to the development of some type of relay not now contemplated? To sum up, it seems that the door of opportunity is still open for the development of a system of protection for transmission lines more satisfactory than any now in use.

**G. A. Powell:** This paper is a very timely addition to distance relay literature. The curves shown on Figs. 8 to 12 will materially reduce the calculations necessary to determine whether or not distance relays in a given location are liable to cause unnecessary tripping. The relaying of the interconnection between the New York City system and the Niagara-Hudson system involved the study of this problem. A large number of curves almost exactly like the ones shown on Fig. 5 of the paper were drawn. These curves showed conditions for different circuit loads both above and below the transient stability limits for different types of faults. A study of these curves showed that if distance relays were used at all of the stations on the 2-circuit interconnection, unnecessary and undesirable separations would occur under oscillating conditions on the remaining circuit immediately following the tripping of one of the circuits due to a fault.

Various modified schemes of directional relaying were studied including a combination of distance directional and standard power directional relays which limited the phase angle through which the distance relay could trip its switch. In addition, the distance relay was to be designed so that, after a definite time delay, the angle through which it normally operated was automatically changed in an effort to prevent its operation during load swings. This scheme appeared fairly satisfactory except that under some out-of-step conditions, tripping would occur at stations where it was not desired to trip. Furthermore, correct operation of this scheme involved a race between the different relays with small margins of time and phase angle.

From the knowledge gained in the above study, I am not sure that the authors' proposed use of a true power relay as a blocking relay, even if its action is delayed, will make it desirable to use distance relays in all cases. In practical application it will be difficult to obtain a watt and a time setting for the blocking relay which will give the desired results, particularly where relays must be set to give satisfactory protection with single line operation as well as double line operation. I believe it highly desirable to separate at some predetermined point depending upon system connections, and for this reason agree with the authors that for automatically separating under out-of-step conditions the use of an out-of-step relay especially designed for the purpose offers the best solution. Having provided this relay for out-of-step tripping at a predetermined point, it would be highly objectionable to have the distance relays at some other station trip at the same time as the out-of-step relay.

The use of the carrier current pilot relaying scheme appears to offer the most dependable relay scheme for protecting important circuits which are subject to oscillating and out-of-step conditions. The addition of an independent out-of-step relay to the standard directional relays controlled by carrier would make this scheme almost ideal.

**G. W. Gerell:** Previous to the construction and interconnection of the Osage Hydroelectric plant in 1931, experiences with unstable systems had been rather meager. It was well recognized that we would not be immune to these troubles unless proper remedial measures were taken to eliminate them. All new circuits and equipment were, therefore, provided with high speed relays and oil switches, and all of the existing circuits comprising the major transmission system were similarly equipped. It was believed that high voltage buses and radial feeders should also be provided with high speed protective equipment, but it could not be economically justified at that time.

For reference in the following discussion a one line diagram of the major 60 cycle transmission system is shown (Fig. 1). During the last 3 years of operation of this system there have been 3 cases of trouble resulting in an unstable condition. In all 3 cases the fault occurred on the 66-kv system, one also involving the 13.8-kv system at the Page Ave. station, and under such conditions that the high speed relays did not have an opportunity to function. The faulty circuits in each case were properly isolated, but, in addition, the impedance relays on the Osage-Page lines operated to clear this circuit at both ends. The reactance relays at the Cahokia station on the Rivermines lines also operated in 2 instances.

The results of an a-c calculating board study for one particular case showed that the system actually became unstable. Determination of current and voltage relations at the relay stations explained the operation of the impedance relays on the Osage-Page lines and also the operation of the reactance relays on the Rivermines lines at Cahokia. All instability cases which we have experienced have occurred for faults electrically close to the Venice station, and in each case the distance relay operations have been identical and at relay stations nearest

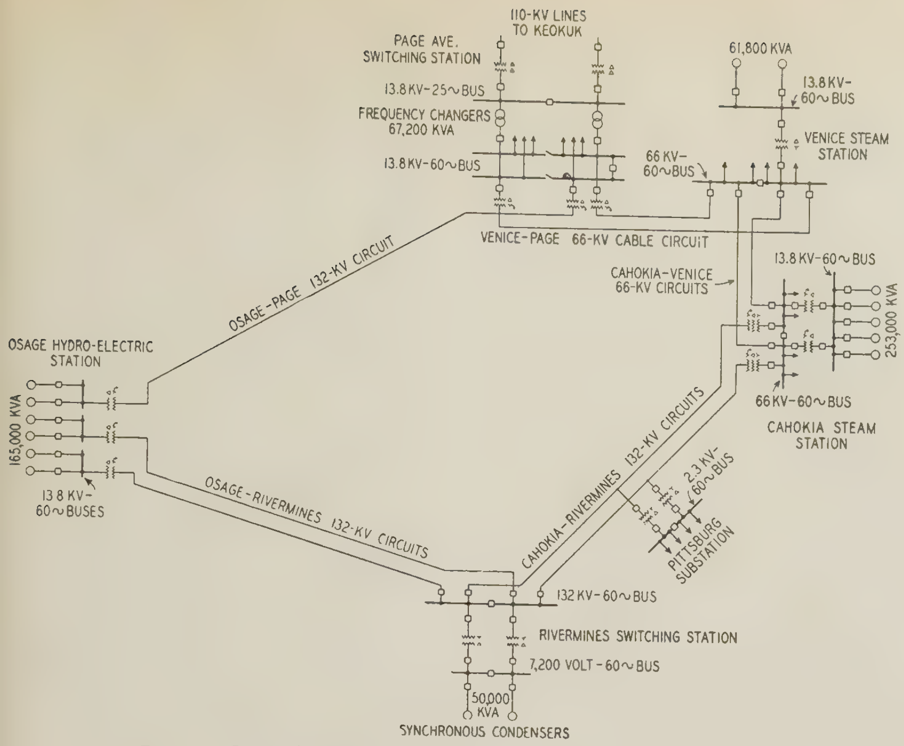



**Fig. 1. General plan of the 66- and 132-kv transmission systems**

to the fault, although outside of the section upon which the fault occurred.

In order to prevent the recurrence of such troubles on our system, we have endeavored to provide high speed relay equipments at all points which were not previously equipped at the time of the Osage interconnection. This included the installation of differential protection on the 66-kv buses at Cahokia and Venice and the installation of high speed ground relays to a number of radial feeder circuits from these buses. A number of other improvements have been made on the relay system, particularly in regard to the high speed protection of transformer banks.

At the present time, our protective equipment will, with very few exceptions, clear faults on the 66- and 132-kv systems in less than 0.3 second. Most transmission line faults are isolated in 0.15 second with negligible disturbance to the system. Stability studies substantiated by recent experiences indicate that switching times of this order are amply fast to prevent instability of the system during fault conditions. Incidentally, it is of interest to note that several automatic oscillographs located at strategic points have been invaluable in providing us with data concerning instability phenomena and have been the basis upon which several improvements were made to the relay system.

**H. R. Stewart:** May I call attention to an additional matter which has been experienced on one or 2 systems when an unbalanced fault on a low tension bus or feeder has been delayed in clearing, with the result that the 2 ends of the system reached a 180 deg out-of-phase condition before the fault was cleared. Under this condition the positive sequence voltage at one end of the system is opposite and approximately equal to that at the other end of the system and passes through zero at the electrical center; the negative sequence voltage is zero at the 2 ends, and is a maximum at the point of fault. Therefore, there is a zone where the negative sequence voltage exceeds the positive sequence voltage, giving the effect of reversed phase rotation of the voltage. The result of this is incorrect operation of one or more of the relay directional elements at each line terminal in this zone, with consequent increased undesirable tripping of breakers if the associated distance elements are also in position to trip.

I note that in comparing the action of reactance and impedance relays under out-of-step conditions, the authors use a setting on the impedance relay of equal sensitivity to that of the starting unit of the reactance relay. In view of the fact that in practice the starting unit of the reactance relay is set to reach out over approximately $2^1/_2$ line sections, and is thus set more sensitively than an impedance relay which is set to reach out over 80 per cent of a line section, is the comparison of practical value? Should not the comparison be made on the basis of settings which would be used under operating conditions?

**Giuseppe Calabrese:** The rapid increase in the number of interconnections which has taken place in the past years has made it evident that protective relays should operate correctly, not only during faults, but during swings and out-of-step conditions as well. Thus it is gratifying that a paper such as the one presented by Messrs. Bancker and Hunter should be submitted before the Institute. The analysis made during the past 10 years of the problem of stability and the factors affecting it has led to operating improvements and increased service continuity. The stability analysis, however, has stopped at the point where the machine either remains in step or loses synchronism. To my knowledge, with the exception of a few sporadic papers, no systematic analysis is available of what happens afterward. I believe, therefore, that its extension to cover the period after synchronism is lost would be useful as it would undoubtedly lead to additional improvements, probably as important as those brought about by the systematic study of the stability problem.

A short time ago, the engineers of the New York Edison and the Niagara-Hudson systems were faced with the same problem as that treated by the authors, in studying the protection of the 132-kv interconnection between these 2 systems. A detailed analysis of a scheme of protection with distance relays of the reactance type was made. It was found that the scheme, though satisfactory during faults, would have given rise under certain conditions to incorrect tripping during swings. Furthermore, during out-of-step conditions, the separation of the 2 systems might have occurred at points other than the desired ones. For these reasons, the scheme was abandoned altogether and the high frequency carrier protection was used. The details of the protection of this interconnection will be described in a paper that is planned for submission before the Institute in the near future.

One point I wish to emphasize concerning the performance of distance relays during swings and out-of-step conditions is the effect of the current transformer connections. The performance of the directional unit and the ohms indicated by the ohm unit depend on the potential and current transformer connections as well as on their ratios and relay location. As an illustration, there may be mentioned the case of a reactance relay used on a pure reactance tie line between 2 systems of equal internal voltage. In such a case, the reactance center and the electrical center coincide. If the current transformers are connected in delta, the ohm indication during swings and out-of-step conditions is equal to the reactance of the tie line between the relay location and the reactance center. This is evident from Fig. 2 in which $E$ is the magnitude of the line to neutral voltages of systems Nos. 1 and 2; $\theta$ the angle by which system No. 1 leads No. 2 at the instant considered; $I$ the current flowing from system No. 1 to No. 2; $E_r$ the line to neutral voltage at the relay location; $X_r$ reactance of the tie between the location of the relay and the reactance center; $\theta_r$ the angle between $E_r$ and $I$. With potential and current transformers both connected in delta, the ohms measured by the relay are proportional to $\dfrac{\sqrt{3}\,E_r}{\sqrt{3}\,I}\sin\theta_r$ that is, to $X_r$, as seen from the triangle $RCO$ in Fig. 2. If the settings of the relay are smaller than this reactance, the relay will never trip during swings and out-of-step conditions. If the potential transformers are connected in delta and the current transformers in wye, the ohms measured by the relay during swings and out-of-step conditions are proportional to $\dfrac{\sqrt{3}\,E_r}{I}\sin(\theta_r + 30°)$. With this connection, therefore, the ohms which the relay measures are not constant but vary as the angle be-

tween the 2 systems changes and may become less than the value for which the relay is set, thus resulting in an undesirable tripping operation.

Another point I wish to discuss concerns the use of a true power relay with circuit opening contacts to block out distance relays in order to prevent tripping during swings. It is stated that the setting of the true power relay should be "high enough so that there would be no danger of blocking on high resistance faults." It is assumed that the high resistance faults referred to in the paper are arcing faults, involving 2 or 3 conductors. Of course, arcing faults involving 2 conductors are unbalanced. As to arcing faults involving all 3 phases, it seems highly improbable that such faults will ever be balanced. In those few cases, when they occur, in all probability they are unbalanced. Therefore, as all unbalanced faults produce negative sequence voltages,

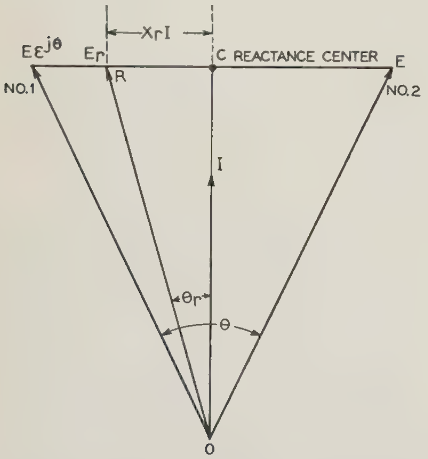



**Fig. 2. A reactance relay example assuming a pure reactance tie line between 2 systems of equal internal voltage**

it would be entirely feasible to avoid the undesirable high setting of the power relay by paralleling the trip contacts of the latter with those of a sensitively set negative sequence relay with circuit closing contacts, both sets of contacts being connected in series with those of the reactance relay. With this arrangement, the pick-up of the true power relay must be only high enough to prevent the relay from picking up with 3-phase dead short circuits. All unbalanced faults, 2 phase or 3 phase, would be detected by the distance relay through the contacts of the negative sequence relay, irrespective of the action of the true power relay. Three-phase dead short circuits would be detected through the contacts of the true power relay. Power swings above the setting of the true power relay and out-of-step conditions would not cause incorrect trippings regardless of the ohms measured by the distance relay, as the negative sequence relay would be inoperative and the true power relay energized, thus blocking the trip circuit of the distance relay. During power swings below the pick-up of the true power relay, the distance relay would not be blocked out. However, with the power relay pick-up maintained sufficiently low, these swings would be but small and therefore would not cause distance relays to pick up.

The curves showing the performance of impedance and reactance relays under various operating conditions should be of great assistance in the application of protective equipment. It would be very helpful if the authors had given the formulas on which the curves are based in order that their limitations may be more clearly understood.

Referring to the method suggested by the authors for calculating the maximum stable angle, also not specifically stated in the paper, I assume that whenever an initial and a final condition are involved, the calculation must be made on the basis of the final and not on the basis of the initial condition.

Regarding out-of-step relays as applied to interconnections between 2 large systems, it may be mentioned that with the high frequency carrier scheme of protection, it is possible, under favorable conditions, to incorporate the out-of-step feature in the scheme itself without additional equipment other than that required by consideration of protection against faults. This was found to be possible in the case of the interconnection between the New York Edison and the Niagara-Hudson systems and will be described in detail in the paper under preparation.

**E. H. Bancker and E. M. Hunter:** The authors are entirely in sympathy with the suggestion made by Messrs. Adams, Powell, and Calabrese that the best solution to avoid false operation of distance relays during swings is the use of a pilot system of relaying instead. Some pilot systems would be entirely impervious to either oscillation or out-of-step currents, while others which would not inherently be immune can be rendered so. The suggestion of a change to a more stable form of relaying as a solution was not included in the paper as its purpose was primarily to assist in studies of distance relays already in use and to suggest such remedial measures as might be applied in case they were found to be in any danger of tripping incorrectly.

The authors also subscribe fully to Mr. Gerrell's commendation of the use of automatic oscillographs. Prior to their adoption, any analysis of what actually happened during system disturbances was much more a matter of guesswork and conjecture than of real knowledge. Even the comparatively few automatic oscillographs now in use have been almost invaluable in giving fundamental information from which a real analysis of the events which occur throughout the disturbance might be made.

Mr. Stewart questions the utility of the comparison made in Fig. 7 between impedance relays having equal sensitivity with the starting unit of reactance relays. The purpose of this comparison was chiefly to bring out the effect of relay location upon the 2 types of devices and naturally such effect could be studied much more easily if the relays were brought to a common basis in all other respects. However, the behavior of the starting unit of a reactance relay is a rather difficult matter to describe because its minimum operating amperes are a function of both volts and power factor, both of which change with relay location. The impedance relay is affected only by voltage which, of course, changes with location. Because of the double effect of location upon the reactance relay starting unit, it may under fault conditions be able to cover about 2 line sections (9.6 ohms) and yet be no more sensitive to swings than an impedance relay set for 4.8 ohms, a setting which might be required on a long line. Hence the starting unit will cover 2 or more line sections as Mr. Stewart says and the impedance relay is set only for the impedance of its own line section, and yet under oscillating conditions the 2 have equal sensitivity. For any real study, however, the actual settings of the relays should be used in conjunction with Figs. 8 to 12.

Mr. Calabrese's statement regarding the use of final conditions is correct. The usual cause for a system oscillation is a short circuit and it is presumed that the faulted line will be disconnected by its protective relays. Therefore, the determination of the maximum stable angle must be made with the faulted line out of service, or as Mr. Calabrese says, using the final condition of system set-up.

Curves of the paper were actually calculated from the pickup current vs. voltage curves of the different elements. This is the only convenient way of deriving the curve for the *GAX* type because of its nonlinear potential coil circuit. The linear circuits of the impedance and *GCX* relay starting units make it possible to give an equation for them. For the impedance relay, the minimum operating current expressed as a function of the displacement angle, the relay location with respect to the electrical center, and the setting of the relay is given by the following equation:

$$I = \frac{\sqrt{\left(\cos\frac{\theta}{2}\right)^2 + \left(\frac{x}{X}\sin\frac{\theta}{2}\right)^2}}{Z}$$

where $\theta$ is the displacement angle; $\frac{x}{X}$ is the per-unit relay distance from the electrical center, and $Z$ is the maximum impedance for which the element is set.

For the *GCX* starting unit using the same terminology, the minimum operating current is

$$I = \frac{\left(\cos\frac{\theta}{2}\right)^2 + \left(\frac{x}{X}\sin\frac{\theta}{2}\right)^2}{9.6\,\frac{x}{X}\sin\frac{\theta}{2}}$$

It may be of interest to note in connection with this element that the maximum sensitivity is attained by a relay located at such a point that the angle between the relay voltage and the voltage of the electrical center is 45 deg. This figure obtains regardless of the total displacement angle, so that the location of the most sensitive relay during a swing progresses from some imaginary point outside of the generator side of the system down to the electrical center.

As stated in the text of the paper, the curves apply to relays so connected that the maximum torque occurs at the natural angle of lag of the system using either wye volts and amperes or delta volts and amperes. Calculations can be made of the action of relays using delta volts and wye amperes, but they are complicated by the addition of the 30-deg displacement angle mentioned by Mr. Calabrese.

# Iron Shielding for Telephone Cables

**Discussion and authors' closure of a paper by H. R. Moore published in the February 1934 issue, p. 274–80, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.**

**I. C. Forshee and K. L. Maurer:** In connection with the electrification of the Philadelphia-Norristown section of the Wilkes-Barre division of the Pennsylvania Railroad in 1930, the railroad's open-wire communication circuits were replaced by an aerial tape-armored lead sheath cable, similar in make-up to the cables described in the paper, in order to secure protection against voltages induced by the electrification. This aerial installation, about 16 miles in length, extends over the greater part of the electrified section. The cable is paper insulated and contains 12 quads of No. 13 AWG conductors. The lead sheath has a nominal thickness of $1/8$ in., an outside diameter of $1^9/_{16}$ in., and is covered with a double layer of spirally wound galvanized steel tapes 0.043 in. thick and $1^3/_4$ in. wide. Sheath and armor are bonded together at every splice and both are connected to the electrified tracks through signal impedance bonds at intervals of 1 to 2 miles. On account of the relatively small size of the cable sheath, additional shielding was provided for by placing 2 4/0 copper shield wires on the same pole line about 18 in. above the cable. These shield wires also are connected to the tracks at impedance bonds.

The electrification system consists of an 11,000-volt 25-cycle trolley over each of the 2 tracks and 2 25-cycle 132-kv transmission lines on the same structures that support the trolleys. The communication cable and a braid covered signal cable are each suspended from a steel messenger carried on wood poles just outside the catenary supports.

Before the electrification was placed in operation, a number of tests in which the American Telephone and Telegraph Company coöperated were conducted to determine the merit of this arrangement of shields in limiting voltages induced in the communication circuits. A test section about 1,500 ft long was used, at the ends of which insulating joints were cut into the cable sheath and armor, and insulators in the 2 cable messengers and the 2 shield wires. Inside the test section, with the exception of the tape armored cable and its messenger, all metallic connections between the shields were removed. With one of the trolleys energized to the tracks at low current over most of the electrified section, the 25-cycle induced voltages in the communication conductors were measured with the shields successively in and out of the circuit. These tests showed a shield factor for the entire combination of 0.44 for the induced voltage referred to the tracks and 0.30 for the induced voltage referred to ground connections about 100 ft away from the tracks. This shield factor was observed with a testing current of approximately 30 amp in the trolley, and the figure is thus for the condition of low current in the sheath of the tape armored cable. With sheath currents that would correspond to operating conditions or short circuit conditions on the electrification, the contribution to the total shielding made by the tape armored cable would be considerably larger than under the test conditions so that the combined shield factor would be expected to be smaller than the above test factors. It was not possible under the test conditions available to determine precisely what proportion of the total shielding was contributed by the tape armored cable. Indications are, however, that under the test conditions, the shield factor due to the tape armored cable alone was about 0.6 with voltages referred to the tracks and something less than this with voltages referred to a ground independent of the tracks. From laboratory tests made by Mr. Moore on a sample of this cable (sample No. 11 in Table I of the paper), it is estimated that under normal operating conditions on the electrification the 25-cycle shield factor of the tape armored cable by itself would average about 0.4, and under short-circuit conditions about 0.2.

Under the field test conditions, the shielding was larger for voltages referred to ground connections independent of the track return system than for voltages referred to the track return system. This condition results from the fact that with the shielding system connected to the tracks the shielding current under the test conditions was determined partly by induction along the sheath and partly by the potential difference between track and ground. With the circuit for measuring voltage in the cable conductors completed through the tracks this voltage is the same as that producing the shielding current, but if the circuit is completed through ground connections independent of the tracks the conductor voltage is produced chiefly by the induction along the cable, which in this case was smaller than the voltage imposed on the sheath. In general, the difference in shield factors for the 2 reference points of conductor voltage will depend, among other things, upon factors which control the voltage to ground of the tracks, chief among which are the self-impedance of the tracks, their leakage conductance to ground, and length of energized section. If the energized trolley, the cable sheath, and the conductors are of equal length, the ratio of shield factor for voltages referred to tracks to that for voltages referred to independent grounds ranges from unity for very long feeding distances through a maximum value which may be as much as 4 or 5 under average conditions as to ballast resistance, to a value considerably less than unity for very short feeding distances.

The results obtained with this shielding arrangement during approximately 4 years of service have been very satisfactory from the communication standpoint in the limitation of induced voltages and freedom from service interruptions from this source.

Another installation of aerial, tape-armored cable on the Pennsylvania Railroad was used to replace open-wire conductors on the concrete pole line across the New Jersey meadows between Newark, N. J., and the west end of the Hudson River tunnels to New York. In addition to the tape armored cable, this pole line carries an unarmored lead sheath cable, a braid covered signal cable, and a 4/0 copper shield wire which is carried on pin type insulators on top of the wood crossarm from which the cables are suspended. The tape armored cable has a lead sheath 0.151 in. thick with an outside diameter of $2^7/_{16}$ in., over which is wound a double layer of galvanized steel tape 2 in. wide and 0.044 in. thick. The plain lead sheath cable has a sheath thickness of $1/8$ in. and outside diameter of $2^1/_{32}$ in. The features of the electrification system and the exposure of the communication circuits are similar to those described for the Wilkes-Barre division.

Tests conducted jointly as on the Wilkes-Barre division were made over a section of this line about 3 miles long. At the terminals of this section provision was made for connecting the cable sheaths and shield wire to the track return system through impedance bonds. Measurements were made of 25-cycle induced voltage with the previously mentioned shields connected singly or in groups and with one trolley, coterminal with the test conductors and shields, energized with a current of about 35 amp. Shield factors observed under the test conditions were as follows: tape armored cable alone, 0.52; lead sheath cable alone, 0.69; shield wire alone, 0.44 to 0.53; and all shielding conductors in parallel, 0.31 to 0.38. The induced voltages in all cases were referred to ground connections about 200 ft from the tracks. For the length of section used in this test, the shield factors would have been larger had the voltages been referred to the track return system. It will be noticed that the shield factor for the shield wire ranges below the shield factor for the tape armored cable. This is undoubtedly due to the fact that the latter was measured at a low value of sheath current and it would be expected that at values of sheath current obtainable under normal load or short-circuit conditions, the tape armored cable would compare much more favorably with the shield wire.

With regard to the use of the track return system instead of ground connections independent of the tracks for completing the shielding circuit for tape armored cables and shield wires, it is the view of the Pennsylvania Railroad that with the former the effectiveness of the shielding system is, in general, increased. The track return system in most of the electrified sections involves a plurality of heavy, well-bonded rails in parallel, the conductivity of which is augmented by copper ground wires on the catenary structures, conditions which limit voltages imposed on the shielding structures due to potential difference between track and ground. The equivalent of low resistance ground connections is obtained with ease and the necessity and expense of installing and maintaining driven ground connections are avoided.

**L. P. Ferris:** It is of interest to examine how charts of Moore's paper may be utilized for the rapid solution of specific problems of the kind discussed in the paper by Gilkeson and Hanks.

The inductive exposure discussed in the Gilkeson-Hanks paper is 20 miles long, capable of giving longitudinal induced voltages at the location proposed for the communication conductors of 18,600 volts

for the worst fault condition on the power line and 170 volts for the worst normal operating condition. The corresponding voltages per 1,000 ft are 176 and 1.6. The frequency is 60 cycles. It was desired to reduce the longitudinal voltage on the communication conductors to something less than 900 volts under abnormal conditions and to less than 5 volts under normal conditions. Thus, shield factors of 0.048 for abnormal induction and 0.029 for normal induction are required. The problem is, in essence, to find a practical design of armored cable which will give these or better shield factors.

If it be assumed that a cable of approximately full size would be required to carry the desired number of communication conductors plus auxiliary conductors paralleled with the sheath, and that the sheath is grounded at the ends of the exposure, Fig. 5 of Moore's paper is directly applicable. With a disturbing field of 176 volts per 1,000 ft and the corresponding desired shield factor of 0.048, there is found for the resistance of the sheath, plus grounding resistance $\left(r_{22} + \frac{R}{l}\right)$, a value of 0.063 ohm per 1,000 ft. For induction under normal operating conditions of 1.6 volts per 1,000 ft and the corresponding required shield factor of 0.029, Fig. 5 gives the resistance as 0.015 ohm per 1,000 ft. Obviously, therefore, the normal induction is the controlling factor in determining the permissible resistance of the cable sheath. If it be assumed that the sheath is grounded through connections of negligibly low resistance, the sheath resistance itself must not exceed 0.015 ohm per 1,000 ft, to obtain which there would be required about 580,000 cir mils of copper in parallel with the normal lead sheath. This is but slightly larger than the value worked out by Gilkeson and Hanks. Returning to Fig. 5 with this sheath resistance of 0.015 ohm per 1,000 ft and the 176 volts per 1,000 ft induced under abnormal conditions, there is found a shield factor of about 0.012, again in good agreement with the figure derived by Gilkeson and Hanks.

From a developmental standpoint, it is to be regretted that the proposed installation has not materialized so as to afford an opportunity for an experimental check on these estimates.

**H. R. Moore:** Although more than 500 miles of steel tape armored communication cable have been installed in this country, there have been as yet only a few instances in which the choice of this construction was based upon a need for its unique shielding properties. Hence, it has been of considerable interest to study the report of I. C. Forshee and K. L. Maurer on 2 installations of armored cable specifically intended to protect communication circuits from induction due to an electrified railway. Because of the high traction currents the protection of circuits located on the railway right-of-way definitely requires shielding of the order provided by the steel armored cable. Extensive use of this type of cable has been made in Europe also, notably in Germany and in Sweden, under such conditions.

Two errors have been found in the printed text of the paper: The unit applying to the symbol $t$ in the list following eq 3 should be inches rather than mils. In Figs. 7 and 8, the units for the quantity $l\sqrt{G}$ should be (mho ft $\times$ 1,000)$^{1/2}$ rather than (mho per 1,000 ft)$^{1/2}$.

# Iron Armored Aerial Communication Cable

**Discussion and authors' closure of a paper by C. L. Gilkeson and A. J. Hanks published in the June 1934 issue, p. 890–5, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.**

**A. E. Bowen:** In the paper by Messrs. Gilkeson and Hanks the authors say that their "problem is to determine the most economical combination of iron armoring and copper shielding capable of providing the desired degree of reduction." While they arrived at a cable design which would yield the desired shielding it is not at all certain that the recommended cable is the most economical one. Looked at critically the problem which the authors set and answered was: "Given a cable sheath of fixed dimensions, armored with iron tapes of fixed dimensions and magnetic characteristics, what amount of copper placed within and connected in parallel with the sheath will supply the desired amount of shielding?" To this restricted problem the authors have supplied an answer, but the more general problem is considerably more difficult and has by no means been solved.

If, in the design of a cable for a given application, the adjustment of the copper-lead-iron balance is given complete latitude, there may be considered as variables:

For the iron tapes. Number, thickness, width, spacing (or angle of lay), permeability, and resistivity.

For the lead sheath. Thickness.

For the copper shield wires. Number, gauge, and angle of lay. (Alternatively, tapes or rectangular wires might be considered.)

A fixed dimensional factor is the inner diameter of the copper as determined by the required group of communication conductors and their insulation, while only those combinations are eligible which yield a specified shield factor for a specified field intensity. The latter condition demands the additional specification of the earth return impedance of the cable sheath and its grounding resistances.

From the purely electrical standpoint, the array of possible variations in design features is formidable. If there are considered at the same time the mechanical consequences of changes in the size and method of spiralling of the copper wires or iron tapes, as is necessary to insure a cable of feasible characteristics, the complications are multiplied. Finally, determination of the most economical design from among all of the possible constructions capable of affording the required shielding would require interrelated studies of costs of materials and manufacture involving a most intricate balance. It may be concluded that, with the information now available, it is not practical to determine what construction is the *most* economical.

Preliminary experimental studies by the Bell Telephone Laboratories of means for improving the shielding other than by paralleling the sheath with copper have indicated that much could be gained by modification of the armoring, which, in the present cables, was designed primarily from mechanical considerations. With the same amount of steel, so wound as to diminish the air gap between turns and annealed to develop greater permeabilities, it is expected that the improvement in the shielding may be such as to substantially reduce the amount of auxiliary copper required. Further benefits are possible by changes in the composition of the steel. Some of these possibilities have also been investigated experimentally by Zastrow and Wild of the Siemens Halske Company (*E.N.T.* 1932, v. 9, p. 10).

**K. L. Maurer:** The paper by Messrs. Gilkeson and Hanks is an interesting example of inductive coördination planning in advance of construction of one of the facilities involved in an inductive relationship. Field tests on several actual installations of tape armored aerial cable with which I am familiar have indicated the general reliability of the formulas and data upon which the calculations in the paper are based, and there appears to be no reason why the large estimated reduction factor for the cable design worked out by the authors could not have been realized in practice. It is thus a striking illustration of the possibilities in special cable design to incorporate protection against outside disturbing influences.

In the section dealing with direct contacts between a faulted phase conductor and the cable sheath several statements would appear to need a certain amount of qualification. It is mentioned that in the event of such a contact the cable sheath would be raised in potential to earth by an amount equal to the product of the fault current and the impedance of the cable sheath to ground, and that this potential difference would also exist between the sheath and the conductors inside at the point of contact but not along the conductors nor at their terminals. The first of these statements is correct if the faulted phase wire and the cable sheath are so situated in relation to one another that there is no inductive coupling between them. This condition might be realized, for example, by a contact at a right angle crossing of a cable and an a-c power line. Under these circumstances the voltage of the cable sheath above earth would be equal to the product of the total current entering the sheath and the impedance of the sheath to ground at that point. However, this voltage will, in general, not exist between the cable sheath and the internal conductors at the point of contact, the latter also being elevated in potential above earth by reason of the voltage induced in them by the current on the cable sheath. The voltage between the sheath and the conductors at the point of contact will depend on a number of factors among which are the electrical constants of the sheath-earth circuit, the leakage conductance of the sheath to ground, and the length of the cable either way from the point of contact. If the cable sheath and conductors extend for considerable distances beyond the point of contact or if the conduc-

tors are connected to ground through terminal apparatus the potential between sheath and conductor at the point of contact will be the integrated resistance drop in the cable sheath. For the cable described in the paper this quantity would be expected to be a relatively small part of the voltage of sheath to ground so that the voltage of conductor to ground at the point of contact would be expected to be of the same order of magnitude as the voltage of sheath to ground.

If the power line is parallel to and not widely separated from the cable, which is understood to be the arrangement applying to the situation considered in the paper, the potential to ground assumed by the cable sheath in the event of a cross would be influenced by the voltage induced in the cable sheath by residual power line current on either side of the point of contact. For the same total fault current and the same cable sheath conditions as in the right angle crossing case, the voltage to ground at the point of contact would, in general, be expected to be lower. The voltage between cable sheath and conductors at the point of contact also would be influenced by the coupling with the faulted power conductors on each side of the contact. These relationships can readily be formulated in terms of the distributed constants of the cable and the mutual impedance between the power line and the cable. These expressions are rather cumbersome, and as their formulation depends on the physical arrangement of the systems involved with regard to such things as length of power and communication lines, single versus 2-way power feed, location of fault, etc., they are not given here.

With regard to the calculated values of sheath to ground voltage given in the table at the end of the section dealing with this question, it would appear from the above considerations that the voltage figures would not also apply to the potential between sheath and conductors. The large difference in sheath to ground voltage depending upon whether the contact is in the middle of a span or at a tower seems surprising, in view of the relatively short spans (15 towers per mile, or about 350-ft spacing on the average). If these potentials are taken as the product of the fault current and the impedance of the sheath to ground, the earth-return impedance of the sheath apparently would have to be between 11 and 12 ohms per mile to account for the difference in voltage for the 2 points of contact.

**C. L. Gilkeson:** Mr. Maurer comments on the large difference in the computed voltage to ground for the condition of a contact in midspan and at a tower. The reason for this difference is that these calculations were not based on the average span of 350 ft, but on the maximum span of 600 ft. The longer span, of course, represents the more unfavorable condition.

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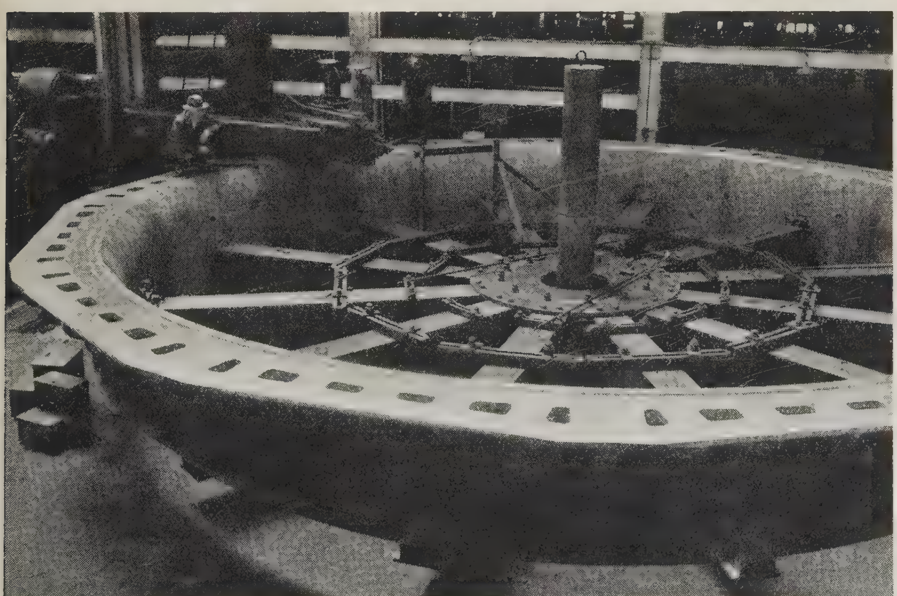
## Throat Liners of the Boulder Dam Penstocks



A RECENT photograph taken as machinists in the shops of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., prepare to "face off" the throat liners of the huge penstocks to be used at Boulder Dam. The tool in the left background makes the desired cut in the face of the casting, 2 minutes being required for each complete revolution. After being "faced off," 912 holes are drilled through the 2-in. thickness of the steel. Ten days are required for this latter operation on the boring machine, which had to be improvised to accommodate the casting's unusually large size. The steel casting weighs 40 tons, and is 36 ft in outside diameter.

## Recent Developments in Power Line Carrier

**Discussion of a paper by T. Johnson, Jr., published in the April 1934 issue, p. 542–7, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.**

**R. C. Buell:** The unit construction employed in the carrier telephone equipment described in Mr. Johnson's paper makes it possible to utilize this apparatus for carrier applications other than telephone. In the operation of power systems, carrier very frequently offers means of supervisory control, remote indication, and relaying which have outstanding advantages in economy and reliability. The most important of these applications of carrier has been pilot relaying of transmission lines. For most power systems pilot relaying surpasses all other forms of protection in the speed with which all line faults can be cleared. Carrier is of particular advantage as a pilot channel, not only because of the economies it offers but because of its inherent reliability; it is in use only when the transmission line is conducting power current to an external short circuit, and under this condition the continuity of the carrier channel is absolutely assured.

The use of power line carrier as a simple solution to remote control problems is illustrated by the instance of an operating company which had a long high-voltage power line tapped by another circuit some distance from the generating station. The usual substation with oil circuit breakers and associated equipment could not be justified and only air break disconnect switches were installed in the circuits. Due to the inaccessible location of these disconnect switches, it often took a patrolman 2 or 3 hours to reach the switches when trouble occurred on this line. In order to facilitate restoration of service, the 2 disconnect switches were motor operated from a battery and a time delay undervoltage relay was installed to open the air break disconnect switches in case of power failure. Carrier current was used to send a tripping impulse over the power line to reclose the disconnect switches one at a time at the discretion of the operator. Now, when the line gets in trouble, the operator tests the line to the disconnect switches, and, if O. K. that far, he closes first one and then the other disconnect switch, locating the section in trouble and restoring service to the good section.

In another case, a load dispatcher wanted to be able to vary the load on an automatic hydroelectric station, so a simple carrier transmitter was installed at his office, and a receiver at the station. When the operator wants to increase the load at the station he pulls a switch in one direction which energizes the carrier current transmitter on each positive half cycle of the 60-cycle power system. The receiver at the station picks up a relay and starts opening the gates as long as the carrier is transmitted. When the operator desires to decrease the load he pulls the switch in the opposite direction, sending out carrier on the negative half cycle which runs the gates toward the closed position.

# News
## Of Institute and Related Activities

## A.I.E.E. Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., on August 7, 1934.

Present: *President*—J. Allen Johnson, Buffalo, N. Y. *Past Presidents*—J. B. Whitehead, Baltimore, Md.; and H. P. Charlesworth, New York, N. Y. *Vice President*—W. H. Timbie, Cambridge, Mass. *Directors*—F. Malcolm Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; Everett S. Lee, Schenectady, N. Y.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y.

The minutes of the board of directors meeting held June 27, 1934, were approved.

A resolution in memory of Past President Harris J. Ryan, who died on July 3, 1934, was adopted, as appearing elsewhere in this issue.

A report was presented of a meeting of the board of examiners held July 25, 1934, and the actions taken at that meeting were approved. Upon the recommendation of the board of examiners, the following actions were taken: 7 applicants were elected and 16 were transferred to the grade of Member; 57 applicants were elected to the grade of Associate; 75 Students were enrolled.

The finance committee reported monthly expenditures, as follows: July, $18,128.34; August, $13,504.51. Report approved.

Upon recommendation of the committee on Student Branches, authorization was given for the organization of a Student Branch of the Institute at Brown University, Providence, R. I.

Announcement was made of the appointment by the President of committees for the administrative year beginning August 1, 1934; and representatives of the Institute on various bodies were appointed by the board for the new year. (List of committees and representatives appear elsewhere in this issue.)

In accordance with the by-laws of the Edison Medal committee, the board confirmed the appointments to the committee made by the president, as follows: C. E. Stephens as chairman for the year 1934–1935, and H. B. Gear, L. C. Nichols, and J. B. Whitehead, for terms of 5 years each; and the board elected from its own membership, for terms of 2 years each, F. M. Farmer, Everett S. Lee, and A. C. Stevens.

Complying with the by-laws of the Lamme Medal committee, the board confirmed the president's appointment of C. E. Skinner as chairman for the year beginning August 1, 1934, and of L. E. Imlay, F. B. Jewett, A. M. MacCutcheon as members of the committee for terms of 3 years each.

C. O. Bickelhaupt (chairman), F. J. Chesterman, J. Allen Johnson, William McClellan, and C. E. Stephens were reappointed representatives, and H. H. Henline, alternate, of the Institute on the assembly of American Engineering Council for the year 1935.

The following local honorary secretaries were reappointed for the 2-year term beginning August 1, 1934: V. J. F. Brain, for Australia; A. S. Garfield, for France; H. P. Thomas, for India; and W. Elsdon-Dew, for Transvaal.

Report was made of the appointment, upon the nomination of the standards committee, of the following representatives: R. C. VanSickle as a member of the Institute delegation on the Sectional Committee on Power Switchgear, A.S.A. Project No. C-37; and W. C. White as one of the Institute's representatives on the Sectional Committee on Radio, A.S.A. Project C-16.

An invitation was presented to nominate a person for the award of the 1935 Kelvin Medal, and the president was authorized to appoint a committee to recommend nominees to the board of directors.

Decision was made to hold the next meeting of the board of directors on Friday, October 19, 1934.

Other subjects were discussed, reference to which may be found in this or future issues of Electrical Engineering.

## Future AIEE Meetings

**Winter Convention,**
New York, N. Y., Jan. 22–25, 1935

**South West District Meeting,**
Oklahoma City, Okla., Apr. 26–28, 1935

**Summer Convention,**
Ithaca, N. Y., June 24–28, 1935

**Pacific Coast Convention,**
Los Angeles vicinity, Fall 1935

**Great Lakes District Meeting,**
Indianapolis—Lafayette Section territory (Date to be determined)

## President of A.S.T.M. Dies

William Hastings Bassett, newly elected president of the American Society for Testing Materials, died on July 21, 1934, only 3 weeks after assuming his new office. He was born at New Bedford, Mass., on March 7, 1868. He graduated from Massachusetts Institute of Technology with the degree of B.S. in 1891, and after various chemical work joined the Ohio Brass Company in 1903 as chief chemist, becoming technical superintendent and metallurgist in 1912 and metallurgical manager in 1930.

Mr. Bassett was a pioneer metallurgist in the brass industry, and was among the first in the United States to apply microscopy to the metallography of non-ferrous metals, and likewise the spectroscope to routine work in the industry. He was a past-president of the American Institute of Mining and Metallurgical Engineers and a former director of the American Institute of Chemical Engineers. Other societies in which he held membership included the American Chemical Society, The American Society of Mechanical Engineers, Society of Automotive Engineers, American Electrochemical Society, Mining and Metallurgical Society of America, American Geographical Society, Franklin Institute, Institute of Metals of London, England, and Society of Chemical Industry of London, England. His son, W. H. Bassett, Jr. (M'30) is technical superintendent and metallurgist, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

## Ford to Install Second 110,000-Kw Generator

A second 110,000-kw turbine generator is to be installed by the Ford Motor Company at its River Rouge power plant at Fordson, Mich., similar to, but even more efficient than the one installed there in 1930. The new machine, like the first, is a vertical compound unit, and the high pressure turbine and generator will be mounted directly on top of the low pressure turbine and generator. Each element has a capacity of 55,000 kw, and rotates at 1,800 rpm. The rating of the combined unit is 110,000 kw, 80 per cent power factor, 13.8 kv, 3 phase, 60 cycles, with steam conditions of 1,200-lb gauge pressure, 900-deg F total temperature, and one inch absolute back pressure. Because of the high initial temperature, it is not necessary to reheat the steam before it goes into the low pressure unit, as had to be done in the case of all 1,200-lb turbines built heretofore.

As a result of the high temperature, less than a pound of coal will be needed to generate the kilowatthour. One of the important features of the vertical design will be the small amount of space taken by the unit,

the general dimensions being 57.5 ft by 23 ft, with 21 ft over-all height from the floor. The weight will be approximately 1,000 tons.

For the same station, a 15,000-kw non-condensing turbine is being obtained to furnish process steam to the Ford factory at 250 lb pressure. Both units are being built by the General Electric Company.

## Former Chairman of Boston Section Dies

W. Irving Middleton, who for many years was active in the electrical industry, died at his home in Watertown, Mass., on April 27, 1934. He was a specialist in insulation, and was chief electrical engineer of the Simplex Wire and Cable Company, Boston, Mass., until poor health caused his resignation from his position and from the Institute 2 years ago. Mr. Middleton was born at Lowell, Mass., February 9, 1870. He joined the Simplex organization in 1903, and was instrumental in the development of the sine wave generator. He was elected an Associate in 1909, and a Member in 1914.

Mr. Middleton presented a number of papers before the Institute, and was chairman of the Boston Section in 1920–21. He was one of the founders of the Insulated Power Cable Engineers Association, and a member of the National Electric Light Association, the American Engineering Standards Committee, and the Engineers' Club of Boston.

**Major Armstrong Appointed Professor at Columbia University.** Major Edwin Howard Armstrong, famed for his discoveries in radio communication, and a central figure in a celebrated patent controversy which after nearly 2 decades still engages the attention of the United States Supreme Court, has been appointed professor of electrical engineering at Columbia University. Major Armstrong will direct instruction in radio communication and high frequency research in the Hartley laboratory, which will be incorporated into the department of electrical engineering, of which Prof. W. I. Slichter (A'00, F'12, and national treasurer) is the head. The Hartley laboratories have been the scene of many of the accomplishments of Prof. M. I. Pupin (A'90, F'15, HM'28, member for life, and past-president), as well as of the early efforts of Armstrong in the development of the vacuum tube oscillator. Professor Pupin will continue his researches in these laboratories. As announced by Dean J. W. Barker (M'26, F'30) of the school of engineering, the appointment of Major Armstrong fills the vacancy created by the death last winter of Prof. J. H. Morecroft.

## In Memoriam

THE death, on July 3, 1934, of Dr. Harris J. Ryan removed from the American Institute of Electrical Engineers its thirty-sixth President and a member who had throughout his career, participated enthusiastically in its activities.

Upon beginning his life work as an engineering teacher only 2 years after his graduation, in 1887, from Cornell University, he immediately displayed one of his most notable characteristics, an impelling desire to ascertain through experimental research the basic scientific facts needed to give his students a clear understanding of the fundamental principles involved in the various types of electrical equipment. In 1889, he presented his paper on the transformer, which received wide attention and was the first of a long series of technical papers presenting the results of pioneer research in many divisions of electrical engineering. As head of a department of electrical engineering during nearly the whole of his career, he constantly brought to his administrative duties and to his work in the classroom great enthusiasm and breadth of vision supported by a vast store of technical information developed through his studies and experimental researches.

HARRIS J. RYAN

His ability, his delightful personality, his keen enthusiasm in the advancement of scientific knowledge and in the education of young engineers, his continuing interest in the problems encountered by his graduates, and his outstanding contributions to the development of the electrical industries made him a highly respected leader, and won the affection of all who knew him.

Professor Ryan joined the Institute in 1887, and was transferred in 1895 to the grade of Member and in 1923 to the grade of Fellow. He served on many Institute committees, represented it upon other bodies, and was manager 1893–96, vice president 1896–98, and president 1923–24. He was awarded the Edison Medal in 1925.

RESOLVED: That the board of directors of the American Institute of Electrical Engineers hereby expresses, upon behalf of the membership, its deep sorrow at the death of Dr. Ryan, and its keen appreciation of his many contributions to its activities, and be it further

RESOLVED: That these resolutions be entered in the minutes and copies be transmitted to members of his family.

—A.I.E.E. Board of Directors, August 7, 1934

## Annual Science Exhibition of A.A.A.S.

The annual science exhibition of the American Association for the Advancement of Science and associated societies will be held in Pittsburgh, Pa., December 27–30, 1934. The exhibit will be in the new building of the Mellon Institute for Industrial Research. This building is probably one of the finest pieces of architecture in the United States.

The science exhibition is expected to be by far the greatest ever held by this organization, and is the single outstanding feature of the meetings to be held concurrently with the exhibits. Free exhibition space is available for those exhibits or demonstrations which are found acceptable. Some of the special attractions already arranged are demonstrations on cosmic rays, deuterium, neutrons, induced radioactivity, stratosphere flights, and a series of demonstrations of recent advances in physics. Requests for information should be made to F. C. Brown, director of exhibits, American Association for the Advancement of Science, Smithsonian Institution Building, Washington, D. C.

## Additional Awards for 1933 Institute Papers

In addition to the national and District prizes for papers presented before the Institute during the calendar year 1933, as announced in ELECTRICAL ENGINEERING for June 1934, p. 1026, and August 1934, p. 1234–5, announcement now has been made of the award of 2 additional prizes. These are:

DISTRICT NO. 2

Prize for best paper awarded to Maxwell K. Goldstein (A'33) for his paper "Telemetering in Large Power Stations," presented before the Baltimore Section, May 19, 1933.

DISTRICT NO. 8

Prize for best paper awarded to Lloyd F. Hunt (A'21) and Alex A. Kroneberg (A'26) for their paper "Some Recent Relay Developments," presented before the Los Angeles Section, December 12, 1933.

## Membership—

The Section membership committees have been continuing their activities during the summer months and the results are as follows:

Applications for membership received during May, June, and July, 1933 . . . . . . . . . . 71

Applications for membership received during May, June, and July, 1934 . . . . . . . . . . 135

We need the help of every member of the Institute in our membership work. As a member you can do 2 things:

1. Be appreciative of the program of your Section membership committee and give of your time to it as you can.
2. Send to the Chairman of your Section membership committee the names of those whom you think should be invited to join the Institute.

Chairman National Membership Committee

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Engineering Education for Non-Engineers

*To the Editor:*

The primary purpose of secondary education is to fit the graduate to live up to the full capacity of his potentialities, adequately adjusted to the environment in which he finds himself. The present civilization in which we are now living is an engineering civilization, the chief landmarks of which are our so-called modern conveniences. Man's present day environment is permeated with engineering achievements in which the forces and materials of nature have truly been yoked for his benefit. It is well-nigh impossible to pick out any detail of man's daily routine that is devoid of dependence upon engineering. From the time he rises from his bed in the morning, until he retires at night, he unknowingly finds himself totally dependent upon the ingeniousness of the engineer. The worst calamity that an Asmodeus could wreck upon humanity would be to remove the past 50 years of engineering progress from our present civilization and leave us with only those conveniences which existed at that time. If a civilization is to exist at all, it must be a progressive civilization; a dormant or retrogressive civilization eventually leads to annihilation. A progressive civilization is one that is dominated by the results of engineering achievements, each achievement based upon former achievements, and each one a little better than those which have gone before. Civilization is thus in a state of flux, with a slowly and constantly progressive trend toward something a little better. Civilization's progress is intimately linked with engineering progress; these 2, in fact, being synonomous. Man's present environment in which he lives, moves, and has his being, is thus an engineering environment, and his secondary education should, therefore, fit him to live in such an environment.

It is putting the matter conservatively to say that a large percentage of all male students in the colleges do not know why they are there, what they are headed for, or what they are interested in. They do not know what they want to do after leaving college, therefore they do not know what course to pursue while in college. The result is that very often they select a hit-or-miss set of courses (outside of the required courses) with enough easy ones to make certain of accumulating an abundance of credit units toward graduation. And that is the way they prepare to meet the problems of life; they feel that the best bet probably is to take a general course which will fit them for anything in general, but nothing in particular.

Since the world in which the graduate must live and earn a living is so pervaded with things engineering, what better selection could he make to adjust himself to his environment than to take an engineering course? A college course in engineering will come nearer to fitting him for our present civilization than any other choice he could make; it is an ideal "general course" and will put him in a better position to strike out for a livelihood than any other general course he could devise. This is true no matter whether he finally becomes a butcher, banker, business man, or what not. Because he takes an engineering course does not necessarily mean that he must practice engineering upon graduation. He can enter any line of business and will find that his rigorous training in analytical thinking based upon facts will stand him in good stead for success in that business.

Too many practicing engineers today advise young men to take any course in college but engineering, with the thought in mind that an engineering course is good for nothing else other than the practice of engineering. The first thought that comes to mind is, "There are already too many engineers, so why encourage more?" and they never stop to consider that an engineering training might possibly be good for something other than the practice of engineering. If more men were encouraged to take engineering with the broad idea in mind of preparing for life and not necessarily for engineering alone, the engineering profession would receive a much greater appreciation for its services and would not be in such a sad plight of non-recognition as it is today. No one appreciates the problems of engineering better than engineers themselves, consequently, if more of our business men had engineering training, the profession of engineering would be much more highly appreciated.

The complaint that an engineering course is too narrow and devoid of the necessary liberalizing subjects to make it a good general course, is groundless. The average engineering curriculum permits a goodly number of elective courses to be selected from the departments of economics, English, history, psychology, sociology, etc., so that by and large the engineer's training becomes fairly liberal. The engineering curriculum requires considerably more credit hours than the general or arts curriculum, and very frequently the number of elective hours almost equals the number of hours required for one year's work in the arts course, making it possible for the engineering student to carry the equivalent of almost a whole year of liberal arts. It is difficult to conceive of a more ideal college course than the engineering curriculum with electives in liberal arts. Such a course not only prepares the student to live in and contribute the most to this present age, but it automatically builds up a greater appreciation for the engineer and the engineering profession.

Very truly yours,
W. J. SEELEY (A'19, M'28)
(Professor of Electrical Engineering, Duke University, Durham, N. C.)

# Personal Items

J. B. Fisken (A'03, F'13, and member for life) safety engineer, The Washington Water Power Company, Spokane, was honored by the Institute's Spokane Branch by the presentation of a resolution commemorating his 21 years of activity in the founding and building of the Branch. The presentation was made at a meeting celebrating the 50th anniversary of the Institute and the 21st of the Branch. Mr. Fisken has been intimately connected with power development in Washington since 1887. He was an Institute manager, 1916–19, and a vice president, 1919–20, and has served on the following committees: public policy (now Institute policy), 1916–17; sections, 1917–18, 1920–22; economics of electric service, 1919–20; and membership, 1928–29.

Philander Betts (A'96, F'13, and life member) has resigned as chief engineer of the New Jersey Board of Public Utility Commissioners after 24 years' service, and will engage in private practice. Previous to his connection with the commission he was engaged in the construction of power plants and street railways and as a government engineer at Washington, D. C. During the war he became a lieutenant colonel, later becoming a colonel in the engineers reserve corps. He has served on several Institute committees: board of examiners, 1914–16 and 1921–23; economics of electric service, 1914–19; meetings and papers (now technical program), 1915–17; and safety codes, 1924–30.

L. F. Morehouse (M'16, F'20) equipment development engineer, American Telephone and Telegraph Company, New York, N. Y., has had the degree of doctor of engineering conferred upon him by the University of Michigan in recognition of his contributions to telephone engineering. He has been engaged in communication engineering since 1906. Mr. Morehouse has been very active in Institute affairs, having been a manager 1919–23 and a vice president 1924–26, and has been on 13 committees.

J. C. Damon (A'05, M'13) formerly engineer in the construction department of Jackson and Moreland, Boston, Mass., is now chief engineer with the Public Service Commission of Wisconsin, where he has given special attention to the continuous inventory plan for public utilities. He served on the power transmission and distribution committee of the Institute from 1925 to 1927.

M. M. Samuels (F'24) formerly with the J. G. White Engineering Corporation, New York, N. Y., has been appointed economic analyst of the rate survey being made by the Federal Power Commission. Mr. Samuels was a member of the Institute's power generation committee from 1924 to 1927.

W. A. Hillebrand (A'08, M'13) professor of electrical engineering, University of California, Berkeley, Calif., has been elected secretary of the San Francisco Section of the Institute for 1934–35. He served on the power transmission and distribution committee 1925–26 and 1933–34.

J. B. FISKEN

John Morse (A'09) general superintendent, Shawinigan Water and Power Company, Montreal, Que., Canada, has been elected president of the Canadian Electrical Association for the coming year. Mr. Morse is a member of the general power applications committee of the Institute.

G. T. Shoemaker (M'20) vice president, United Light and Power Engineering and Construction Company, Davenport, Iowa, has been named assistant general manager in the United Light and Power Company, Davenport. He will continue his former duties in the subsidiary company.

E. A. Baldwin (A'07) vice president, International General Electric Company Inc., Paris, France, has been designated by the American government as an official observer to the eighteenth session of the International Labor Conference now in session at Geneva.

C. H. Keel (A'09, M'13), patent attorney specializing in electrical and automotive patents, New York, N. Y., has been elected secretary of The New York Patent Law Association for 1934–5. Mr. Keel is a member of the firm of Bartlett, Eyre, Scott, and Keel.

G. C. Shaad (A'03, F'13) dean, school of engineering and architecture, University of Kansas, Lawrence, was elected a vice president of the Society for the Promotion of Engineering Education at the annual meeting held in June at Ithaca, N. Y. He was a vice president 1930–32.

C. J. Hawkes (M'26) engineer, The Electric Storage Battery Company, Seattle, Wash., has been lecturing on recent developments in storage batteries before each of the 4 Northwest Sections.

C. F. Himes (A'34) electrical department, Stanolind Pipe Line Company, Haven Kans., received the 1933 A.I.E.E. South West District prize for Branch paper and not the North Eastern District prize as announced in the August 1934 issue.

H. S. Lane (A'12, M'30) assistant engineer, Pacific Gas and Electric Company, San Francisco, Calif., has been elected a member-at-large of the Institute's San Francisco Section. He was a member of the communication committee 1933–34.

J. F. Porter (A'87, F'33, and member for life) president, Kansas City Power and Light Company, Kansas City, Mo., has received an honorary degree in electrical engineering from Iowa State College, Ames, of which he is a graduate.

W. J. S. Dormer (A'25, M'31) division toll plant engineer, Bell Telephone Company of Canada, Montreal, Que., for the past 5 years, has been appointed district engineer, Three Rivers and Montreal suburban districts.

H. C. Hamilton (A'23, M'26) superintendent, standardizing and testing department, Edison Electric Illuminating Company of Boston, Mass., has been elected vice chairman of the Boston Section of the Institute.

T. R. Langan (A'13, M'30) northeastern district manager, Westinghouse Electric and Manufacturing Company, New York, N. Y., has been elected a director of the New York Electrical Society.

Donald Rhodes (A'30) division transmission engineer, Bell Telephone Company of Canada, Montreal, Que., for the past 2 years, has been appointed district engineer of the Sherbrooke district of that company.

C. W. Leihy (A'30) publishing director, *Electrical West*, McGraw-Hill Company of California, San Francisco, Calif., has been elected a member-at-large of the Institute's San Francisco Section.

D. D. Smalley (A'20, M'33) distribution superintendent, Midland Counties Public Service Corporation, Santa Maria, Calif., has been elected a member-at-large of the Institute's San Francisco Section.

G. J. Crowdes (A'21, M'32) electrical engineer, Simplex Wire and Cable Company, Cambridge, Mass., has been elected chairman of the Boston section of the Institute.

J. B. Kobrock (A'13, M'26) assistant to the general manager, New England Telephone and Telegraph Company, Boston, Mass., has retired as chairman of the executive committee of the Engineering Societies of New England.

H. I. Finch (A'03, M'13) former president of the Emerson Electric Manufacturing Company, St. Louis, Mo., has become chairman of the board of that company.

C. A. Corney (A'16, M'20) assistant superintendent, electrical engineering department, Edison Electric Illuminating Company of Boston, Mass., is chairman of the executive committee of the Engineering Societies of New England.

P. O. Noble (A'19, M'28) has been appointed engineer of the fractional horsepower motor engineering department, of which he was formerly assistant engineer, of the General Electric Company, Fort Wayne, Ind.

A. F. Welch (A'12, M'27) former engineer of the fractional horsepower motor engineering department of the General Electric Company, Fort Wayne, Ind., has been appointed consulting engineer of that department.

F. W. Bliss (A'30) district manager, sales development department, General Electric Company, Boston, Mass., is a member of the executive committee of the Engineering Societies of New England.

C. E. Wilson (A'16) electrical erecting engineer, General Electric Company, Schenectady, N. Y., has been elected a director of the Electric Household Utilities Corporation.

J. M. Murray (A'29) electrical engineer, Simplex Wire and Cable Company, Cambridge, Mass., has been elected secretary and treasurer of the Boston Section of the Institute.

W. G. Stearns (A'09) formerly with the General Cable Company, is sales representative for The Okonite Company in San Francisco, Calif.

H. A. Smith (A'03) division manager, Wisconsin Power and Light Company, Fond du Lac, Wis., for the past 2 years, is now in charge of special development work for the same company in Madison, Wis.

A. M. Bohnert (A'12, M'26) district engineer, Ohio Brass Company, San Francisco, Calif., has been elected chairman of the Institute's San Francisco Section for 1934–35.

E. M. Wright (A'20, M'31) assistant engineer, Pacific Gas and Electric Company, San Francisco, Calif., has been elected vice chairman of the Institute's San Francisco Section for 1934–35.

R. O. Brosemer (A'31) General Electric Company, San Francisco, Calif., has been elected a member-at-large of the San Francisco Section of the Institute.

G. F. Fowler (A'29) Bell Telephone Laboratories, Inc., New York, N. Y., has been elected treasurer of the New York Electrical Society.

J. B. Bassett (A'13, M'23) assistant district engineer, General Electric Company, New York, N. Y., has been elected a director of the New York Electrical Society.

# Obituary

Herbert Aubrey Barre (A'11) chief engineer, Southern California Edison Company, Ltd., died on June 28, 1934, as the result of a cerebral hemorrhage. He was born at Picton, Nova Scotia, Canada, on January 26, 1875. After his graduation from the University of California in 1897 he was employed by several power and transit companies in California until in 1902 he became assistant to a Los Angeles, Calif., consulting engineer. Four years later he was again engaged with power companies, and in 1908 came to New York, N. Y., as engineer with the Electric Operating Construction Company. He returned to California 3 years later as electrical-mechanical engineer for the Pacific Light and Power Corporation, a company later acquired by the Southern California Edison Company. Mr. Barre became executive engineer of the latter company in 1917 and chief engineer in 1929. He was largely responsible for the construction and operation of the first 150,000-volt long-distance transmission line in the world, that between the Big Creek–San Joaquin development and Los Angeles. This line was converted under his supervision for 220,000-volt operation in 1923. He served the Institute on the transmission and distribution committee, 1915–17, and the power generation committee, 1920–27. Mr. Barre was also a member of The American Institute of Mechanical Engineers.

Samuel Groenendyke McMeen (A'95, F'12, and member for life) retired consulting engineer of Pasadena, Calif., died on June 22, 1934. He was born at Eugene, Ind., Nov. 28, 1864. He left Purdue University, Lafayette, Ind., to work for the Central Union Telephone Company in 1884, becoming assistant chief engineer at Chicago, Ill., in 1896. In 1902 he accepted a position as engineer in the central office equipment department of the Western Electric Company, Chicago, Ill. Two years later with the late K. B. Miller he formed the firm of McMeen and Miller in Chicago, consulting engineers in telephone systems, and patent experts. For this firm Mr. McMeen designed and constructed the automatic telephone systems in San Francisco, Oakland, and Berkeley, Calif. In 1912 he entered public utility management, and was president of the Mount Hood Railway and Power Company, Portland, Ore.; Columbus Railway Power and Light Company, Columbus, Ohio, Ohio State Telephone Company; and East St. Louis railway, light, power, and gas properties. He was vice president and director of similar properties in Tennessee, and was also chairman of the board of directors of the North Electric Manufacturing Company, Galion, Ohio, from 1918 to 1922. He was a member of the Naval Consulting Board in 1916. Mr. McMeen was an inventor of many devices used in the telephone and automotive arts. In conjunction with others he wrote "Telephony," "American Archery," and the "American Handbook for Electrical Engineers," and was author of other technical writings. He served on the Edison Medal committee 1912–17, and was also a member of The American Society of Mechanical Engineers, the Western Society of Engineers, and the American Electric Railway Association.

George Alfred Damon (A'98, F'14) consulting engineer, Pasadena, Calif., died June 23, 1934, of cerebral congestion after an illness of only a few hours. He was born at Chesaning, Mich., April 7, 1870. During 1893 he was employed at the World's Fair in Chicago, Ill., and for a short time by the Fisher Electrical Works, Detroit, Mich., after which he returned to the University of Michigan to complete his course and receive his engineering degree in 1895. Following graduation he was associated with B. J. Arnold (A'92, F'12, past president, and member for life) in Chicago, Ill., as draftsman and engineer. From 1900 to 1907 Mr. Damon was managing engineer of The Arnold Company, engineers and constructors in Chicago, and in this position was in responsible charge of the design of power plants and electrical installations for a number of railroads. In 1907 he was again associated with Mr. Arnold on transit appraisals and reports in New York, N. Y., and Pittsburgh, Pa. He went to California in 1910 and the following year became dean of engineering at the California Institute of Technology, Pasadena, Calif., which position he held until 1914. He then engaged in consulting engineering in Los Angeles, San Jose, and Long Beach, Calif. He was a member of the Pasadena Historical Society, and of the Western Society of Engineers, and a past president of the Society for the Promotion of Engineering Education. He was chairman of the Los Angeles Section of the Institute in 1913.

Arthur W. Dawson (A'19) manager, Michigan Northern Power Company, died recently. He was born Sept. 2, 1877 at Sault Ste. Marie, Mich., and worked first as a lineman for the Bell Telephone Co., then in power house work with the Canadian government. In 1900 he became electrician with the Rhodin Chemical Works for 2 years, then entered the Michigan Lake Superior Power Company as chief operator, one year later becoming superintendent, taking charge a few years later of the electrical installation and operation of a station of the Michigan Northern Power Company, in which he eventually became manager.

Donald Cameron Allison (A'26) manufacturer's representative, Mexico, D. F., Mexico, died in January 1933, according to word recently received at Institute headquarters. He was born at Philadelphia, Pa., on April 8, 1889. In 1907 he was employed by the Mexican General Electric Company, and with the exception of a year in the foreign department of the General Electric Company at Schenectady, N. Y., in 1916, remained in Mexico, becoming assistant manager there in 1925.

# Membership

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Sept. 30, 1934, or Nov. 30, 1934, if the applicant resides outside of the United States or Canada.

Anderson, C. H. (Member), Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Anderson, H. A., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Bangs, N. K., The Fox Paper Co., Lockland, Ohio.
Baum, M., N. Y. Water Serv. Corp., N. Y. City.
Brown, M. K. (Member), Niagara, Lockport & Ontario Pwr. Co., Buffalo, N. Y.
Clancy, C. A. (Member), Niagara Falls Pwr. Co., Niagara Falls, N. Y.
Dunning, O. M., Thomas A. Edison Inc., Orange, N. J.
Eley, F. L., Southern California Edison Co. Ltd., Los Angeles.
Frantz, W. P., Curtis Pub. Co., N. Y. City.
Griffin, G. G., Crouse-Hinds Co., Dallas, Tex.
Hackmann, W. K., Natl. Pwr. Survey, Federal Pwr. Comm., Washington, D. C.
Harrington, H. L. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Holland, G. E., United Elec. Controls Co., South Boston, Mass.
Jeffe, E. F. (Fellow), N. Y. Edison Co. & United Elec. Lt. & Pwr. Co., N. Y. City.
Johnson, E. M., Gen. Elec. Co., Spokane, Wash.
Johnson, R. L., 12 S. Mulberry St., Hagerstown, Md.
Jones, J. D., c/o M. W. Kellogg Co.; Atlantic Refining Co., Philadelphia, Pa.
Kurtz, J. A., J. Kurtz & Sons, Inc., 773 Broadway, Bklyn., N. Y.
Lacallade, C. J., 515 Scotland St., Williamsburg, Va.
Lal, G. D., R. C. A. Victor Co., Inc., Camden, N. J.
Lammers, E. S., Jr. (Member), Westinghouse Elec. & Mfg. Co., Atlanta, Ga.
Leather, Maurice P., Boston Woven Hose & Rubber Co., Cambridge, Mass.
Montgomery, L. A., Imperial Irrigation Dist., Andrade, Calif.
Osborn, R. E., Delco Remy Corp., Anderson, Ind.
Otto, G. A. (Member), The Teleregister Corp., N. Y. City.
Robida, R. E. (Member), Niagara Falls Pwr. Co., Niagara Falls, N. Y.
Sawyer, O. E., New England Pwr. Assoc., Providence, R. I.
Sharp, H. M. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.
Smith, R. L. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Stone, E. W., Central Illinois Light Co., Peoria.
Tice, H. W., So. Calif. Edison Co. Ltd., Los Angeles, Calif.
Ulrey, D., Westinghouse Res. Lab., East Pittsburgh, Pa.
Wagner, E. S. (Member), 205 W. Chocolate Ave., Hershey, Pa.
Wheeler, W. S., P. O. Box 43, Dover, N. H.
Wohlgemuth, A. J., Telautograph Corp., N. Y. City.
Zinter, H. C., Buffalo Gen. Elec. Co., Buffalo, N. Y.
36 Domestic

**Foreign**

Billingham, H. O., Elec. Industries (Pty.) Ltd. Cape Town, So. Africa.
Dawson, George (Member), McMaster-Jacob Engg. Co., Ltd., Toronto, Ont., Canada.
Fethi, S. I., Pwr. House of Kozlu Komuris, Zonguldak, Turkey.
Gautam, S., Upper India Sugar Mills Ltd., Khatauli, Dist. Muzaffar Nagar, India.
Mildner, R. C., Std. Tel. & Cables, North Woolwich, London, England.
Miller, J. L. (Member), Ferranti Ltd., Hollinwood, Lancashire, England.
Panaotovic, P. Gj. (Member), Amer. Yugoslav Elec. Co., Novisad, Yugoslavia.
Thorn, R. C., Taikoo Sugar Refinery, Hong Kong, China.
8 Foreign

## Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloozian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Clark, Merrill C., 161 Madison Ave., New York, N. Y.
Handley, Wilbur H., 4416 Loren Ave., Los Angeles, Calif.
Jordan, Henry, 7408A Christopher Colombus, Montreal, Que., Can.
Losoncy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Mexal, J. Rene, 86–03 Britton Ave., Elmhurst, L. I., N. Y.
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Villegas, Lucio P., Tacoma General Hospital, Tacoma, Wash.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.
13 Addresses Wanted

# Engineering Literature

## New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

DESIGN of MACHINE ELEMENTS. By V. M. Faires. N. Y., Macmillan Co., 1934. 468 p., illus., \$4.00. Those elements of machines which can be designed without using the more complicated theories of strength of materials are presented at the outset, and the chapters then advance to more difficult work. The subject can thus be studied before strength of materials, or concurrently with it. The book covers usual college requirements clearly and practically.

EARTH, RADIO, and the STARS. By H. T. Stetson. N. Y., McGraw-Hill Book Co., Whittlesey House, 1934. 336 p., illus., 8 x 6 in., cloth, \$3.00. An account of our present understanding of the earth in its relations to its cosmic environment using recent developments in astronomy, geology, and radio engineering; the constitution and movements of the earth, the nature of the sun and its radiation, sunspots, and the relation between solar phenomena and terrestrial magnetism and radio transmission are presented.

ELASTICITY, STRUCTURE, and STRENGTH of MATERIALS USED in ENGINEERING CONSTRUCTION, Developed by the Geometry of Strain and the Energy Function through Thermodynamic and Chemical Equations in Such Wise that Strength May Be Figured from Chemical Composition of Rolled Metals and the Modification of This Resistance by Mechanical Work. By C. A. P. Turner. Privately published by the author at 300 Builders Exchange Bldg., Minneapolis, Minn., 1934. 416 p., illus., 10 x 6 in., cloth, \$6.00. Conclusions from many years' study of the theory of resistance. Considerable portions of the author's earlier book, "Elasticity and Strength of Materials," reappear, but the theoretical framework has been further developed.

MACHINE DESIGN. By L. J. Bradford and P. B. Eaton. 3 ed. N. Y., John Wiley & Sons, 1934. 289 p., illus., 9x6 in., cloth, \$3.00. Aims to supply a brief course which can be covered in about 25 lessons, and which will emphasize the fundamental facts and processes of machine design. Revised to conform with recent developments, especially in lubrication and welded construction.

MACHINES AUTOMATIQUES, MÉCANIQUES et ÉLECTRIQUES. (Collection Armand Colin.) By P. Maurer. Paris, Librairie Armand Colin, 1934. 185 p., illus., 7x5 in., paper, 10, 50 frs.; bound, 12 frs. A concise study of the automatization of machines. Bases for a classification of automatic machines and of the general theory of mechanisms are discussed, the processes for making machines automatic are considered, and the chief automatic electrical and mechanical devices are considered.

MECHANICS of ENGINEERING. By S. D. Chambers. N. Y., Macmillan Co., 1934. 279 p., diagrs., 9x6 in., cloth, \$3.50. A class-room text covering only the essentials of statics and kinetics, intended for students of engineering who are acquainted with the elements of the calculus and college physics. The material is arranged to fit one-hour recitations.

MUNICIPAL INDEX, 10th ed. 1933. N. Y. Am. City Mag. Corp. 491 p., illus., 10x7 in., lea. \$5.00. An up-to-date list of city managers, mayors, engineers, water-works and street superintendents and police and fire chiefs in cities over 100,000 in population, and of state highway engineers, together with statistical and other information upon highway construction and maintenance street cleaning, water supply, sewage disposal, traffic control, parks, playgrounds, etc. Condensed catalogs of materials and equipment are also included.

MYSTERIES of the ATOM. By H. A. Wilson. N. Y., D. Van Nostrand Co., 1934. 146 p., illus., 9x6 in., cloth, \$2.50. Concerned chiefly with theories about the microscopic structure of the universe, but large-scale phenomena are considered in chapters on cosmic rays, relativity and gravitation. By omitting technical details, the story has been told briefly, yet with great clarity.

NOTES on LIGHTNING COMPUTATIONS, for Transmission Lines with Overhead Ground Wires. By C. A. Jordan. Privately published by the author at 40 North Spring Garden Ave., Nutley, N. J., 1934. 82 p., illus., paper, \$5.00. Discusses the design of transmission lines with overhead ground wires from the point of view of lightning protection. General solutions are developed for the lightning voltages and currents at critical points, the surge impedances of the various parts of the ground-cloud circuit and the interwire couplings are discussed and, finally, the application of the analytical methods is illustrated by working out a typical problem of high-voltage line design. Published in facsimile typescript, in an edition of 100 copies.

OUTLINES of PHYSICAL GEOLOGY. By C. R. Longwell, A. Knopf and R. F. Flint. N. Y., John Wiley & Sons, 1934. 356 p., illus., 9x6 in., cloth, \$3.00. This is a less comprehensive and somewhat simpler treatment of its subject than that presented in the text published by these authors in 1932. About 2/3 the size of the larger work, it follows the same general plan of presentation and order of subjects, but is adapted to shorter courses.

PROTECTION by PATENTS of SCIENTIFIC DISCOVERIES, Report of the Committee on Patents, Copyrights and TradeMarks. (Occasional Publications of the Am. Assn. for the Advancement of Science, No. 1, Jan., 1934. Supplement to SCIENCE, v. 79.) By J. Rossman, Chairman, F. G. Cottrell, A. W. Hull and A. F. Woods. N. Y., Science Press. 40 p., 10x8 in., paper, \$.50. Discusses very fully the problem of the scientific worker whose researches lead to results of commercial value. Considers the advantages and disadvantages of protecting inventions by patent, and the patent policies of various institutions. Also discusses the desirability of legal protection for scientific discoveries.

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R. W. Atkinson, W. B. Kouwenhoven, O. E. Buckley, Everett S. Lee, L. W. Chubb, F. O. McMillan, E. H. Colpitts, K. W. Miller, E. C. Crittenden, H. H. Race, O. G. C. Dahl, D. W. Roper, W. F. Davidson, T. Spooner, F. Hamburger, Jr., Philip Sporn, H. M. Hobart, C. H. Willis, V. Karapetoff, R. J. Wiseman, A. E. Kennelly, K. S. Wyatt

**Transportation**

C. M. Davis, Chm., General Electric Co., Erie, Pa.
R. Beeuwkes, J. J. Linebaugh, A. H. Candee, E. L. Moreland, J. V. B. Duer, John Murphy, N. E. Funk, N. W. Storer, W. A. Giger, W. M. Vandersluis, W. S. H. Hamilton, Sidney Withington, G. I. Wright

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| Name | District | Chairman | Secretary | Secretary's Address |
|---|---|---|---|---|
| Akron | 2 | R. A. Hudson | H. H. Schroder | 2429 E. Market St., Akron, Ohio |
| Alabama | 4 | H. J. Scholz | H. M. Woodward | Southern Bell Tel. & Tel. Co., Birmingham, Ala. |
| Atlanta | 4 | L. M. Shadgett | W. F. Oliver | Box 2211, Atlanta, Ga. |
| Baltimore | 2 | J. L. D. Speer, Jr. | J. H. Lampe | Johns Hopkins University, Baltimore, Md. |
| Boston | 1 | G. J. Crowdes | J. M. Murray | 66 Sidney St., Cambridge, Mass. |
| Chicago | 5 | D. L. Smith | B. Smith | Illinois Bell Tel. Co., 212 W. Washington St., Chicago, Ill. |
| Cincinnati | 2 | E. J. Jonas | J. T. Bronson | General Elec. Co., 215 W. 3rd St., Cincinnati, Ohio |
| Cleveland | 2 | W. H. LaMond | H. T. Killingsworth | American Tel. & Tel. Co., 750 Huron Rd., Cleveland, Ohio |
| Columbus | 2 | E. E. Dreese | F. W. Marquette | Columbus Ry. Pwr. & Lt. Co., Columbus, Ohio |
| Connecticut | 1 | H. J. Blakeslee | W. B. Hall | Yale University, New Haven, Conn. |
| Dallas | 7 | E. T. Gunther | L. C. Starbird | Telephone Bldg., Room 820, Dallas, Texas |
| Denver | 6 | G. S. Dring | R. H. Owen | National Broadcasting Co., 1370 Krameria St., Denver, Colo. |
| Detroit-Ann Arbor | 5 | J. R. North | H. P. Seelye | Detroit Edison Co., 2000 Second Ave., Detroit, Mich. |
| Erie | 2 | A. S. Goodrich | F. B. Moore | 18 Hess Ave., Erie, Pa. |
| Florida | 4 | R. P. Smith | Joseph Weil | University of Florida, Gainesville, Fla. |
| Fort Wayne | 5 | O. Kiltie | D. H. Hanson | General Elec. Co., 1635 Broadway, Fort Wayne, Ind. |
| Houston | 7 | P. H. Robinson | L. B. Bricker | P. O. Box 1780, Houston, Texas |
| Indianapolis-Laf. | 5 | T. F. Irvine | F. R. Finehout | 5690 N. Delaware St., Indianapolis, Ind. |
| Iowa | 5 | B. S. Willis | H. H. Brown | 3415 First Ave., S. E., Cedar Rapids, Iowa |
| Ithaca | 1 | B. K. Northrop | L. A. Burckmyer | Cornell University, Ithaca, N. Y. |
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| Lehigh Valley | 2 | C. J. MacDonald | Edgar Bell | Pennsylvania Pwr. & Lt. Co., Hazleton, Pa. |
| Los Angeles | 8 | Fred Garrison | O. W. Holden | Bureau of Pwr. & Lt., 207 So. Broadway, Los Angeles, Calif. |
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| Montana | 9 | J. A. Thaler | H. Dale Cline | 312 So. 6th Ave., Bozeman, Montana |
| Nebraska | 6 | T. H. Granfield | C. E. Winn | 1408 W. O. W. Bldg., 14th and Farnum Sts., Omaha, Nebr. |
| New Orleans | 4 | J. M. Todd | F. E. Johnson | 317 Baronne St., New Orleans, La. |
| New York | 3 | W. R. Smith | W. S. Gorsuch | I.R.T. Co., 600 W. 59th St., New York, N. Y. |
| Niagara Frontier | 1 | E. P. Harder | C. E. Gaylord | N. Y. Tel. Co., 63 E. Delavan Ave., Buffalo, N. Y. |
| North Carolina | 4 | H. M. Doerschuk | S. L. Coulter | Box 425, Badin, N. C. |
| Oklahoma City | 7 | A. Naeter | C. E. Bathe | Oklahoma Gas & Elec. Co., Oklahoma City, Okla. |
| Philadelphia | 2 | H. C. Albrecht | J. L. MacBurney | Elec. Storage Battery Co., Philadelphia, Pa. |
| Pittsburgh | 2 | H. A. P. Langstaff | C. A. Powel | Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa. |
| Pittsfield | 1 | L. H. Burnham | C. A. Read | General Electric Co., Pittsfield, Mass. |
| Portland | 9 | Walter Brenton | John Bankus | Portland General Elec. Co., Portland, Ore. |
| Providence | 1 | E. B. Curdts | R. J. Underwood | Narragansett Elec. Co., Providence, R. I. |
| Rochester | 1 | Wm. M. Young | E. H. Branson | General Ry. Signal Co., Rochester, N. Y. |
| St. Louis | 7 | E. G. McLagan | C. O. Campbell | 1322 Pierce Bldg., St. Louis, Mo. |
| San Antonio | 7 | J. W. Farrelly | E. G. Conroy | 107½ Magnolia Drive, San Antonio, Texas |
| San Francisco | 8 | A. M. Bohnert | W. A. Hillebrand | University of California, Berkeley, Calif. |
| Saskatchewan | 10 | J. M. Taylor | F. E. Estlin | Canadian General Elec. Co., Ltd., Regina, Sask., Can. |
| Schenectady | 1 | F. A. Hamilton | Alan Howard | General Elec. Co., Schenectady, N. Y. |
| Seattle | 9 | C. E. Rogers | G. H. Walker | Great Northern Ry. Co., 310 King St. Station, Seattle, Wash. |
| Sharon | 2 | F. J. Vogel | W. A Sumner | Westinghouse Elec. & Mfg. Co., Sharon, Pa. |
| Southern Virginia | 4 | E. L. Lockwood | R. C. Bailey | P. O. Box 112, Richmond, Va. |
| Spokane | 9 | R. H. Hull | M. F. Hatch | Washington Water Pwr. Co., Spokane, Wash. |
| Springfield | 1 | J. W. Bennett | C. G. Veinott | Westinghouse Elec. & Mfg. Co., Page Bldg., Springfield, Mass. |
| Syracuse | 1 | C. H. Bissell | G. E. Tennant | Syracuse Lighting Co. Inc., Syracuse, N. Y. |
| Toledo | 2 | E. J. Rommel | W. M. Campbell | Toledo Edison Co., Toledo, Ohio |
| Toronto | 10 | C. A. Price | R. E. Jones | Hydro-Elec. Pwr. Comm. of Ontario, 620 University Ave., Toronto, Ont. |
| Urbana | 5 | L. L. Smith | H. J. Reich | University of Illinois, Urbana, Ill. |
| Utah | 9 | H. T. Plumb | A. C. Kelm | Utah Pwr. & Lt. Co., Salt Lake City, Utah |
| Vancouver | 10 | F. J. Bartholomew | J. E. Underhill | B. C. Elec. Ry. Co. Ltd., 425 Carrall St., Vancouver, B. C. |
| Washington | 2 | H. G. Dorsey | J. E. O'Brien | Catholic University of America, Washington, D. C. |
| Worcester | 1 | T. H. Morgan | T. R. Holton | 22 Shirley St., Auburn, Mass. |
| Total 61 | | | | |

## Geographical District Executive Committees

| District | Chairman (Vice President, A.I.E.E.) | Secretary (District Secretary) |
|---|---|---|
| No. 1—North Eastern | W. H. Timbie, Massachusetts Institute of Technology, Cambridge, Mass. | A. C. Stevens, General Electric Co., Schenectady, N. Y. |
| No. 2—Middle Eastern | A. M. Wilson, University of Cincinnati, Cincinnati, Ohio | L. L. Bosch, Columbia Engg. Corp., 323 Plum St., Cincinnati, Ohio |
| No. 3—New York City | R. H. Tapscott, 4 Irving Place, New York, N. Y. | C. R. Jones, Westinghouse Elec. & Mfg. Co., 30 Rockefeller Plaza, New York, N. Y. |
| No. 4—Southern | F. M. Craft, P. O. Box 2211, Atlanta, Ga. | S. A. Flemister, P. O. Box 2211, Atlanta, Ga. |
| No. 5—Great Lakes | G. G. Post, 314 Public Service Bldg., Milwaukee, Wis. | A. G. Dewars, Northern States Pr. Co., 15 S. 5th St., Minneapolis, Minn. |
| No. 6—North Central | R. B. Bonney, 1421 Champa St., Denver, Colo. | W. G. Rubel, Mountain States Tel. & Tel. Co., 931 14th St., Denver, Colo. |
| No. 7—South West | F. J. Meyer, Oklahoma Gas & Electric Co., Oklahoma City, Okla. | C. W. Mier, Southwestern Bell Tel. Co., 405 N. Broadway, Oklahoma City, Okla. |
| No. 8—Pacific | R. W. Sorensen, California Institute of Technology, Pasadena, Calif. | J. N. Kelman, Kelman Electric & Mfg. Co., 1650 Naud St., Los Angeles, Calif. |
| No. 9—North West | F. O. McMillan, Oregon State College, Corvallis, Ore. | V. B. Wilfley, 901 Porter Bldg., Portland, Ore. |
| No. 10—Canada | A. H. Hull, Hydro-Electric Power Commission, 620 University Ave., Toronto, Ont. | J. M. Thomson, Ferranti Electric, Ltd., Mount Dennis, Toronto 9, Ont. |

Note: Each District executive committee includes the chairmen and secretaries of all Sections within the District and the chairman of the District committee on student activities.

## Student Branches of the Institute

| Name and Location | District | Counselor |
|---|---|---|
| Akron, Univ. of, Akron, Ohio | 2 | J. T. Walther |
| Alabama Poly. Inst., Auburn, Ala | 4 | W. W. Hill |
| Alabama, Univ. of, University, Ala | 4 | Fred R. Maxwell, Jr. |
| Arizona, Univ. of, Tucson, Ariz | 8 | J. C. Clark |
| Arkansas, Univ. of, Fayetteville, Ark | 7 | W. B. Stelzner |
| Armour Inst. of Tech., Chicago, Ill | 5 | E. H. Freeman |
| British Columbia, Univ. of, Vancouver, B. C | 10 | E. G. Cullwick |
| Brooklyn, Poly. Inst. of, Brooklyn, N. Y | 3 | C. C. Whipple |
| Bucknell Univ., Lewisburg, Pa | 2 | G. A. Irland |
| Calif. Inst. of Tech., Pasadena, Calif | 8 | F. C. Lindvall |
| Calif., Univ. of, Berkeley, Calif | 8 | W. A. Hillebrand |
| Carnegie Inst. of Tech., Pittsburgh, Pa | 2 | G. McC. Porter |
| Case Sch. of Ap. Science, Cleveland, Ohio | 2 | H. B. Dates |
| Catholic Univ. of America, Washington, D. C | 2 | T. J. MacKavanagh |
| Cincinnati, Univ. of, Cincinnati, Ohio | 2 | L. R. Culver |
| Clarkson College of Tech., Potsdam, N. Y | 1 | A. R. Powers |
| Clemson Agri. Col. Clemson College, So. Car | 4 | S. R. Rhodes |
| Colorado State Agri. Col., Fort Collins, Colo | 6 | H. G. Jordan |
| Colorado, Univ. of, Boulder, Colo | 6 | W. C. DuVall |
| Cooper Union, New York, N. Y | 3 | A. J. B. Fairburn |
| Cornell Univ., Ithaca, N. Y | 1 | E. M. Strong |
| Denver, Univ. of, Denver, Colo | 6 | R. E. Nyswander |
| Detroit, Univ. of, Detroit, Mich | 5 | H. O. Warner |
| Drexel Inst., Philadelphia, Pa | 2 | E. O. Lange |
| Duke Univ., Durham, N. C | 4 | W. J. Seeley |
| Florida, Univ. of, Gainesville, Fla | 4 | Joseph Weil |
| George Washington Univ., Washington, D. C | 2 | A. G. Ennis |
| Georgia Sch. of Tech., Atlanta, Ga | 4 | T. W. Fitzgerald |
| Harvard Univ., Cambridge, Mass | 1 | C. L. Dawes |
| Idaho, Univ. of, Moscow, Idaho | 9 | J. R. Hull |
| Illinois, Univ. of, Urbana, Ill | 5 | H. N. Hayward |
| Iowa State Col., Ames, Iowa | 5 | B. S. Willis |
| Iowa, Univ. of, Iowa City, Iowa | 5 | E. B. Kurtz |
| Kansas State Col. Manhattan, Kan | 7 | R. G. Kloeffler |
| Kansas, Univ. of, Lawrence, Kan | 7 | R. W. Warner |
| Kentucky, Univ. of, Lexington, Ky | 4 | E. A. Bureau |
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| Lehigh Univ., Bethlehem, Pa | 2 | N. S. Hibshman |
| Lewis Inst., Chicago, Ill | 5 | F. A. Rogers |
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| Louisville, Univ. of, Louisville, Ky | 4 | J. M. Roberts |
| Maine, Univ. of, Orono, Me | 1 | W. H. Bliss |
| Marquette Univ., Milwaukee, Wis | 5 | F. A. Kartak |
| Mass. Inst. of Tech., Cambridge, Mass | 1 | W. H. Timbie |
| Michigan Col. of Min. & Tech., Houghton, Mich | 5 | G. W. Swenson |
| Michigan State Col., E. Lansing, Mich | 5 | E. E. Kinney |
| Michigan, Univ. of, Ann Arbor, Mich | 5 | S. S. Attwood |
| Milwaukee Sch. of Engg., Milwaukee, Wis | 5 | O. Werwath |
| Minnesota, Univ. of, Minneapolis, Minn | 5 | J. H. Kuhlmann |
| Mississippi State Col., State College, Miss | 4 | L. H. Fox |
| Missouri Sch. of Mines and Met., Rolla, Mo | 7 | I. H. Lovett |
| Missouri, Univ. of, Columbia, Mo | 7 | A. C. Lanier |
| Montana State College, Bozeman, Mont | 9 | J. A. Thaler |
| Nebraska, Univ. of, Lincoln, Neb | 6 | F. W. Norris |
| Nevada, Univ. of, Reno, Nev | 8 | S. G. Palmer |
| Newark Col. of Engg., Newark, N. J | 3 | J. C. Peet |
| New Hampshire, Univ. of, Durham, N. H | 1 | L. W. Hitchcock |
| New Mexico, Univ. of, Albuquerque, New Mexico | 7 | Chester Russell, Jr. |
| New York, Col. of the City of, New York, N. Y | 3 | Harry Baum |
| New York Univ., New York, N. Y | 3 | H. N. Walker |
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| North Carolina, Univ. of, Chapel Hill, N. C | 4 | W. J. Miller |
| North Dakota State College, Fargo, No. Dak | 6 | H. S. Rush |
| North Dakota, Univ. of, Grand Forks, No. Dak | 6 | H. F. Rice |
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| Notre Dame, Univ. of, Notre Dame, Ind | 5 | J. A. Caparo |
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| Ohio Univ., Athens, Ohio | 2 | A. A. Atkinson |
| Oklahoma A. & M. Col., Stillwater, Okla | 7 | Albrecht Naeter |
| Oklahoma, Univ. of, Norman, Okla | 7 | C. T. Almquist |
| Oregon State Col., Corvallis, Ore | 9 | A. L. Albert |
| Pennsylvania State Col., State College, Pa | 2 | L. A. Doggett |
| Pennsylvania, Univ. of, Philadelphia, Pa | 2 | C. D. Fawcett |
| Pittsburgh, Univ. of, Pittsburgh, Pa | 2 | H. E. Dyche |
| Porto Rico, Univ. of, Mayaguez, P. R | 3 | Miguel Wiewall, Jr. |
| Pratt Institute, Brooklyn, N. Y | 3 | C. C. Carr |
| Princeton Univ., Princeton, N. J | 2 | Malcolm Maclaren |
| Purdue Univ., Lafayette, Ind | 5 | A. N. Topping |
| Rensselaer Poly. Inst., Troy, N. Y | 1 | F. M. Sebast |
| Rhode Island State Col., Kingston, R. I | 1 | Wm. Anderson |
| Rice Institute, Houston, Texas | 7 | J. S. Waters |
| Rose Poly. Inst., Terre Haute, Ind | 5 | C. C. Knipmeyer |
| Rutgers University, New Brunswick, N. J | 3 | F. H. Pumphrey |
| Santa Clara, Univ. of, Santa Clara, Calif | 8 | E. F. Peterson |
| South Carolina, Univ. of, Columbia, S. C | 4 | T. F. Ball |
| South Dakota State Col., Brookings, So. Dak | 6 | W. H. Gamble |
| So. Dak. State Sch. of Mines, Rapid City, S. D | 6 | J.O. Kammerman |
| South Dakota, Univ. of, Vermillion, So. Dak | 6 | C. W. Caldwell |
| Southern California, Univ. of, Los Angeles, Calif | 8 | N. C. Clark |
| Southern Methodist Univ., Dallas, Texas | 7 | E. H. Flath |
| Stanford Univ., Stanford University, Calif | 8 | H. H. Skilling |
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| Syracuse Univ., Syracuse, N. Y | 1 | C. W. Henderson |
| Tennessee, Univ. of, Knoxville, Tenn | 4 | J. G. Tarboux |
| Texas A. & M. Col., College Station, Texas | 7 | E. W. Markle |
| Texas Technological Col., Lubbock, Texas | 7 | C. V. Bullen |
| Texas, Univ. of, Austin, Texas | 7 | J. A. Correll |
| Utah, Univ. of, Salt Lake City, Utah | 9 | J. H. Hamilton |
| Vermont, Univ. of, Burlington, Vt | 1 | |
| Villanova College, Villanova, Pa | 2 | H. S. Bueche |
| Virginia Military Inst., Lexington, Va | 4 | S. W. Anderson |
| Virginia Poly. Inst., Blacksburg, Va | 4 | Claudius Lee |
| Virginia, Univ. of, University, Va | 4 | J. S. Miller |
| Washington, State Col. of, Pullman, Wash | 9 | O. E. Osburn |
| Washington, Univ. of, Seattle, Wash | 9 | J. R. Shuck |
| Washington Univ., St. Louis, Mo | 7 | W. L. Upson |
| West Virginia Univ., Morgantown, W. Va | 2 | A. H. Forman |
| Wisconsin, Univ. of, Madison, Wis | 5 | C. M. Jansky |
| Worcester Poly. Inst., Worcester, Mass | 1 | C. D. Knight |
| Wyoming, Univ. of, Laramie, Wyo | 6 | G. H. Sechrist |
| Yale Univ., New Haven, Conn | 1 | W. B. Hall |
| Total 113 | | |

A Student Branch at Brown University, Providence, R. I., was authorized by the Institute's board of directors, August 7, 1934, but at the time of going to press of this issue, had not yet been organized.

# Industrial Notes

**Westinghouse Orders Show Large Increase.**—For the 2nd quarter of 1934, Westinghouse Electric & Mfg. Co. orders totaled $33,655,022, as compared with $20,237,588 for the previous quarter and $17,557,964 for the second quarter of 1933. Sales billed for the second quarter of 1934 totaled $27,287,545, compared to $17,994,045 for the previous quarter, and $15,926,335 for the corresponding quarter of 1933. Unfilled orders at June 30 were $31,892,155 as compared with $24,705,173 on June 30, 1933. According to President F. A. Merrick, orders received for the first half of 1934 show increase of 77% over a similar period in 1933.

**General Radio Co. Opens New York Office.**—The General Radio Co., Cambridge, Mass., announces the opening of an engineering office at 90 West Street in New York City. Engineers from the Cambridge staff have been assigned to this office to assist customers in problems pertaining to radio and electrical measurements.

**Engineering Services Merged.**—Sanderson & Porter, Engineers, with offices in New York, Chicago, and San Francisco, announce the merger of their service for public utility valuation and that of the Cecil F. Elmes organization, to constitute the valuation department of Sanderson & Porter, under the direction of Cecil F. Elmes.

**Burgess Appoints E. A. Sipp.**—Until recently manager of the lighting division of the Pyle-National Co., E. A. Sipp is now associated with the management of the Burgess Battery Co. and C. F. Burgess Laboratories, Inc., and will maintain his headquarters in the offices of the Burgess organizations at 111 W. Monroe St., Chicago.

**Allis-Chalmers Moves Chicago Office.**—The new Field Building, 135 S. LaSalle St., now houses the Chicago district office of the Allis-Chalmers Mfg. Co. B. F. Bilsland is manager of the Chicago district. Thus the company returns to its original Chicago location, for the new Field Building stands on the site of the old Home Insurance Building, where the general offices of the Allis-Chalmers Co. were first located after the company was organized, through consolidations, in the year 1901.

**Delta-Star to Produce Oil-Blast Circuit Breakers.**—The Delta-Star Electric Co., Chicago, reports that it has been granted a patent license by the General Electric Co. to manufacture oil-blast circuit breakers, and has also arranged for the use of the high capacity testing laboratory of the latter company at Schenectady, to conduct tests on these new oil-blast designs. The unit type line of Delta-Star metal-clad switchgear not only includes oil-blast breakers but also the three point balanced circuit breaker mounting, with its single worm gear lifting and lowering mechanism and transfer truck, permitting detanking of breaker for test and inspection without the use of a separate test rack.

**New Engineering Service for Manufacturers.**—Joseph C. Rah & Co., 5745 West Ohio St., Chicago, has recently been organized to render special services exclusively to manufacturers, along the following lines: materials and process engineering; electrical insulation design; mechanical and electrical design; styling; chemical engineering; research, development, and special problems. The new company reports a very favorable response from manufacturers who wish to keep the development and design of their equipment up to date but at the same time do not wish to add full-time specialists to their staffs.

**Electric Locomotives for Penn. R. R.**—Work has been started at the Erie, Pa., plant of the General Electric Co. on electric equipment for 11 new type locomotives being obtained by the Pennsylvania Railroad as part of a new building program which will involve the expenditure of more than $6,000,000. Five of the locomotives will be entirely constructed by the General Electric at Erie; the other equipments will be assembled at the railroad's Altoona works. The new engines will be of the same general type as those now in regular passenger service but the cab has been redesigned to give the locomotive more symmetry of line. The engineman's control will be in the center instead of at the ends of the cab. The locomotives will be part of the fleet of 101 electrics for through-electric passenger and freight service between New York and Washington, to be inaugurated next year.

# Trade Literature

**Sodium-Vapor Lighting.**—Bulletin 3010, 4 pp. Describes the sodium lamp for street and highway lighting. General Electric Co., Schenectady, N. Y.

**Building Wires and Cables.**—Bulletin, 16 pp. Describes Safecote (flame retarding and moisture resistant) braided building wires and cables. General Cable Corp., 420 Lexington Ave., New York.

**Electric Instruments.**—Catalog GEA-602D, 162 pp. Includes complete data on standard lines of switchboard, portable and laboratory instruments. General Electric Company, Schenectady, N. Y.

**Electrically Heated Ladles.**—Bulletin P-57. Describes electrically heated funnel and pouring ladles for waxes, compounds, solder, babbitt, etc. Struthers Dunn, Inc., 139 N. Juniper St., Philadelphia, Pa.

**Oilproof Portable Cords.**—Bulletin, 2 pp. Describes oilproof "Okocord," a Thiokol-sheathed portable cord conductor, insulated with Okonite, particularly designed to meet oily conditions and highly resistant to ozone and corrosive gases and acids. The Okonite Co., Passaic, N. J.

**Air Conditioning.**—Bulletin, 18 pp., "Air Conditioning Planned and Proved." Outlines the factors to be considered in planning air conditioning projects; lists and describes typical installations. Clyde R. Place, Consulting Engineer, Graybar Building, New York.

**Overcurrent Relays.**—Bulletin 41-505, 12 pp. Describes types CR and CRA directional overcurrent relays, primarily to sectionalize transmission lines but used also for the protection of generators subject to feed-back from other sources. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

**Pumps.**—Bulletin 221, 16 pp. Describes multi-stage centrifugal pumps, available with as many as six stages in a single casing. Bulletin 223, 12 pp. Describes motor pumping units, single-stage, single-suction, enclosed impeller types, capacities 50 to 750 g.p.m. Pennsylvania Pump & Compressor Co., Easton, Pa.

**Ladder Mounts.**—Bulletin 376, 24 pp. Describes the Keystone ladder mount and other utility ladders. The ladder mount is a complete extension ladder mounted on a rotating device and arranged to be carried on any small or large truck body. The ladder can be rotated throughout a complete circle and can be rigidly locked in any position. Electric Service Supplies Co., 17th and Cambria Sts., Philadelphia, Pa.

**Armored Service Entrance and Drop Cables.**—Bulletin 100, 4 pp. Describes concentric armored service entrance and service drop cables which are now offered in a complete line of such types. Photographs and tabulations set forth physical characteristics of the designs available, which may be employed in varying combinations to satisfy specific requirements. American Steel & Wire Co., 208 So. LaSalle St., Chicago.

**Brass Die Castings.**—Bulletin, 16 pp., entitled "Brass Die Castings with Strength of Steel." According to this bulletin, intricate brass parts which have heretofore presented a difficult or costly production problem can now be produced economically by die castings, and parts which formerly had to be made in separate units and soldered can now be die cast in a single operation. Doehler Die Casting Co., 386 Fourth Ave., New York.

**Monel Metal.**—Booklet. Describes applications of Monel Metal, nickel, and nickel-clad steel, prepared especially for users of industrial processing equipment. Besides data on the physical and mechanical properties of these materials, the booklet contains considerable miscellaneous information, including instructions on the selection of suitable welding rod and other details on fabrication. The International Nickel Co., Inc., 67 Wall St., New York.